A Resilience-Based Causal Framework for Conducting Safety Analysis

by

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Declarations

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The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Government's Office of the Gene Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

Statement of Co-Authorship

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

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Abstract

A causal relationship is a relative and innate concept that is necessary for reasoning and intervening within an uncertain domain. Almost every field of study has established causal frameworks designed to utilise salient information to satisfy a specific purpose. Due to its comparatively recent maturation and a perceived alignment of purposes, the existing causal framework adopted in formal safety analysis borrows heavily from other fields, such as law and engineering. Although safety methodologies are becoming increasingly sophisticated, their underlying causal assumptions have mostly continued unchallenged despite their direct influence on safety outcomes. Recently, safety methodologies based on the current causal framework have received criticism related to their ability to meet increased public safety expectations when applied to complex socio-technical systems. While these criticisms are justified, they relate to a specific framework of causality rather than the use of causality itself.

Based on the qualitative concepts of Resilience Engineering and Safety-II, this research explicates a new causal framework capable of generating proactive safety recommendations in complex socio-technical systems. Based on this framework, a methodology is developed that utilises a functional decomposition scheme to learn the structure of causal networks. The approach incorporates a broad range of information and focusses on the decisions and tasks required for a system to achieve its purpose. The new methodology is applied to benefit safety in a novel maritime transhipping operation. Implicitly, the approach develops a causally structured reservoir of information relevant to the functioning of the system. This information develops the systems potential to anticipate and respond to variability. Explicitly, the networks act as an oracle for exploring hypothetical contexts and assessing the effect of proposed recommendations.

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Chapter 1 Introduction

1.1. Background

Causality is a primary tool of human judgement. It is the structured approach that allows us to make decisions in an uncertain domain. How we use causality depends on what we are trying to achieve and as such causality is used with incredible diversity. A formal approach to causality was first developed for the purpose of apportioning blame. The use of causality in law required a standardised causal framework to ensure consistent outcomes between legal cases. For a long time, this legal framework devoted to apportioning blame was the sole formal purpose for causality.

During the industrial revolution systems were combining an increasing number of parts to achieve more specialised purposes. To analyse complicated multi-stage systems a new formal approach to causality was implemented. This causal framework decomposed systems into physical aspects, or components that could be treated separately. Now casual notions were being applied to the functionality of machines as well as to the actions of humans. This causal framework assisted with the development of the production line and interchangeable parts and saw system efficiency and functionality increase dramatically.

The need for justice and more efficient and functional systems were, and still are, two differing purposes that require formal application of causal analysis. Both purposes utilise differing causal frameworks to achieve their requirements. The desire not to cause harm was another purpose considered important enough to require formalised causal analysis. This desire is the main driver and purpose of safety and safety analysis.

Until recently safety outcomes could be fulfilled by adopting either the legal of engineering causal framework. Accidents occurred either because a person behaved unlawfully or because a technical component failed. Depending on circumstances, the appropriate causal framework could be applied and there was little overlap or inconsistency. In general, the causal frameworks of law and engineering were mutually exclusive, the mechanisms of technical failures were generally outside the scope of the legal use of causality and the actions of humans were generally outside the scope of causality used by engineers.

However, in the second half of the twentieth century a series of high-profile accidents could not be traced to technological failures or to the inappropriate actions of humans. There were no obvious people to blame and no obvious components to fix. To rectify this, the scope of engineer's causal framework expanded to incorporate the humans as an additional component. Human error, which is the failure of a human to function correctly within the system, became an important research subject. Today a substantial percentage of maritime accidents are cited as being caused by human error (Hetherington et al., 2006). Expanding the scope of reliability analysis brought the engineering causal framework in conflict with the legal causal framework because the actions of humans were now being incorporated into both models for differing, and in some cases conflicting, purposes.

More importantly, the human reliability approach has severe limitations when applied to complex socio-technical systems. This is because, unlike technological components, humans have rarely been designed into systems to satisfy a single purpose. It is far more common to utilise humans to make decisions under uncertainty using contextual information. As systems have become more complex, it is no longer possible to simplify actions to an ideal because knowing what to do is not possible for every situation. The engineering approach of improving or replacing faulty components does not work when humans are applied as decision makers because they cannot be replaced without reducing a system's potential to cope with variability.

A new causal framework is required in safety management. This framework should capture the functionality of complex socio-technical systems and generate outcomes that improve safety beyond the existing causal approach. Thankfully, the qualitative theory for a new approach to the safety analysis of complex socio-technical systems has been developed. In addition, a formal language for expressing and understanding causal relationships has emerged. This study utilises the principles of Resilience Engineering and Safety-II to develop a causal understanding of complex system functionality.

1.2. Objectives and Methodology

The aim of this study is to justify and develop a Safety-II based causal framework and methodology for the safety analysis of a novel maritime transhipping operation. To achieve its aim this study addresses the following research objectives:

- *Identify the role and analyse the importance of causality in safety analysis*
- *Extract the unwritten causal framework underpinning the Safety-II approach*
- *Develop a safety methodology that utilises causality without loss of the conceptual ideals of Safety-II.*

The methodology developed in this study blends the theoretical elements of the functional resonance analysis method (FRAM) and Resilience Engineering with causal Bayesian networks. The FRAM decomposes systems into the functions necessary for it to achieve its goal with special emphasis on functions involving human decision making. Resilience Engineering aims to provide systems with the potential to cope with variability.

A summary of the methodology is given below:

1. Identify the key functions necessary for a system to achieve its purpose.
2. Characterise these functions using the elements of the functional resonance analysis method.
3. Identify the common conditions, i.e. important elements of exogenous variability.
4. Identify potential relationships between common conditions and functions and use these to develop the structure of a causal network.
5. Use the characterised functions to learn the parameters of the causal network.
6. Explore hypothetical contexts to direct further enquiries.
7. Assess the system and intervention through the potential for resilient performance.

1.3. Novel Aspects

This study represents a significant contribution by highlighting the importance of causality in safety science and developing a new causal framework for analysing the safety of complex socio-technical systems. The novel elements of this study can be described as conceptual and methodological, as summarised below:

1.3.1. Conceptual Novelty

1. *Explicating and justifying the role of causality in safety.*

The analysis of safety has always shared a strong connection with causality although it has largely remained unobserved. Although criticisms of the current causal framework have been discussed, this study is the first detailed explication of the role of causality within safety.

Safety researchers and practitioners are very generally divided into two groups: the first, and by far the largest, are those who accept the causal framework currently used. The second, much smaller, group contains researchers who are critical of any causal notions in safety science. While agreeing with the criticisms of the second group, this study advocates and justifies the continued use of causality in safety analysis. This research argues that the criticisms relate to the prevailing causal framework adopted in safety analysis and, that causality in general, is ideally placed to develop and assess safety recommendations.

2. *Establishing and utilising causal modelling as an instrument for Resilience Engineering*

The Safety-II approach advocates evaluating safety by exploring how things normally go right as a prerequisite for considering why they sometimes go wrong. This study develops the connection between the objectives and methodologies of Safety-II and Bayesian causal modelling. This connection has not been developed before.

The act of establishing a causal network that describes the functionality of a system aligns closely with a system's potential for resilient performance. Further, through exploration of hypothetical contexts, a causal network's ability to both direct and assess safety recommendations is established.

1.3.2. Methodological Novelty

3. *Utilising a Safety-II approach to develop causal networks.*

Bayesian networks or causal networks are increasingly being used for safety analysis using the Safety-I approach. However, causal networks have their roots in intelligent information systems and, unlike existing safety and reliability methodologies, were not initially developed to model faults and failures. Despite this, causal networks have not been used from a Safety-II approach. While the functional resonance analysis method has been integrated with causal networks before, this application was essentially a Safety-I approach.

4. *The practical application of a Safety-II approach to benefit a novel maritime transhipping operation.*

Compared to the established Safety-I approach, Safety-II approaches have received relatively little practical application. This study applies the Safety-II approach to a novel maritime transhipping operation. The benefits of this approach compared to a traditional approach are detailed. Part of the reason Safety-II has not received the widespread application it deserves is because existing Safety-II methodologies lack the intuition of causal reasoning. It is hoped that integrating causal notions into the Safety-II approach will help pave the way for more widespread adoption of the Safety-II framework.

1.4. Thesis Outline

This thesis comprises of several chapters intended to be read as a complete body of work. Some of the work contained within this thesis is based on research presented in peer reviewed conference papers however, this thesis does not reproduce these papers.

Chapter 1 provides historical context regarding the use of causality in safety research and establishes the main objectives of this research. Chapter 1 also identifies the novel aspects of the study and presents an outline of the thesis.

Chapter 2 offers an introduction to causality in accordance with how the topic treated within this thesis. Chapter 2 also establishes the importance of causality to human reasoning and decision making especially within an uncertain domain. The chapter also discusses decomposition and emergence and establishes a working definition of a causal relationship. Chapter 2 also details the causal frameworks used in law and engineering. The connection between uncertainty, Bayesianism and causality are established, and causal Bayesian networks are introduced as a tool for developing causal models within an uncertain domain.

Chapter 3 describes and explains the role of causality in safety analysis. The prevailing use of causality in safety analysis is detailed for both risk assessments and accident investigations as are the approaches shortcomings when applied to complex socio-technical systems. The chapter introduces a new approach to safety analysis, known as Safety-II, and presents the arguments raised by Safety-II advocates against the continued use of causality in safety analysis. Chapter 3 concludes by providing a defence of the use of causality in safety science and explains that it is possible to circumvent the shortcomings of the Safety-I approach while utilising the advantages of causal reasoning.

Chapter 4 uses the qualitative methodology of the functional resonance analysis method (FRAM) to structure causal networks from a Safety-II perspective. The approach is applied to benefit a novel maritime operation, the Floating Harbour Transhipper (FHT). First the FRAM and the FHT are introduced. A typical Safety-I risk assessment of the FHT is shown using causal networks. Then the FRAM is used to structure a causal network using the Safety-II approach. Chapter 4 concludes by discussing the differences between the two approaches and the benefits of utilising a functional method of decomposition.

Chapter 5 examines the relationship between causality and resilience and explicates the ability for functional causal networks to develop a system's potential to act resiliently. Chapter 5 introduces the concept of resilience and details the relationship between the four resilient performance potentials and causality. The alignment between developing functional causal networks and the potential for resilience performance is discussed with reference to the Floating Harbour Transhipper safety analysis developed in Chapter 4. Chapter 5 concludes by illustrating the ability to explore hypothetical contexts and direct enquiry using causal networks and the advantages of this approach compared with a traditional risk assessment.

Chapter 6 provides a summary of the conclusions and findings of the study and presents the limitations and assumptions of this research. The potential for future work and the key implications of the research are also provided.

Appendix A provides a summary of the interviews with experts regarding the Floating Harbour Transhipper concept and manoeuvring operation. These interviews assisted in learning the structure of the causal network presented in Chapter 4 and developing recommendations given in Chapter 5.

Chapter 2 Causality and Probabilistic Causal Networks

2.1. Introduction

Causality is an innate concept that forms a pillar of human reasoning. Inferring cause-effect relationships from observations underpins the way we make sense of the world. Due to its ubiquity, the links between causality, explanation and the question 'why' are not immediately apparent. Aristotle defined a cause, verbatim, as an answer to a 'why' question (Falcon, 2008). This definition forms the basis of how causality is used in normal discourse. In short, a cause is an *explanation*.

Causality, as it is often used, conveys a degree of certainty. However, a causal relationship possesses qualities that allow prediction, learning and an understanding of the consequences of actions under uncertainty. Given the importance of these three qualities to our prosperity, it is not surprising that the ability to develop causal relationships is a signature of human cognition.

This chapter links causality with uncertainty and develops the foundations of probabilistic causal networks. Section 2.2 introduces causality and describes its role in allowing us to interact with an uncertain environment. The ability of counterfactuals to explore alternate realities and so to act as a learning tool is discussed in Section 2.3. This is followed by Section 2.4, which explores the key considerations when adopting causal relationships through metaphor. Emergent phenomena and situations where causal explanations are elusive are covered in Section 2.5. Section 2.6 discusses the scope and relativity of causality and proposes an encompassing definition of a causal relationship and the specific causal frameworks of fields such as law and engineering are examined in Section 2.7.

The Bayesian approach to probability is introduced as a language for accommodating and expressing uncertainty in Section 2.8, while Section 2.9 presents an argument for a probabilistic approach to causality. Finally, Section 2.10 introduces causal networks as a tool for modelling causal relationships in uncertain domains.

2.2. Causality, Us and the Truth

Causality is a creation of the mind and is central to human intelligence. Theoretical physics, particularly quantum mechanics, suggests that causality is not axiomatic (Bohm, 1957) and that causal relationships are not a suitable concept for understanding the universe at its most fundamental level.

At their most fundamental level, the laws of nature require no notion of causality, they are symmetrical. Consider Newton's second law, force equals mass times acceleration (F=ma). There is a symmetry to how the law is formulated and, when rearranged, the law works just as well; the law itself is symmetrical. However, causality is attributed to this law. The force, it is said, causes an acceleration rather than an acceleration causing the force. All notions of causality vanish when the same equation is written as the gravitational acceleration between two bodies (as does the notion of a force). If the complete state of the universe along with all its laws were known then the concept of causality would not be needed, things would just be.

Quantum mechanics suggests an asymmetry between the past and the future. However, this asymmetry is a function of temporal ordering and does not rely on notions of cause and effect. The basis for causality's existence as a fundamental fabric of universe is not strong (Dowe and Noordhof, 2004)

Although it was theorised prior to the 20th century that causality was not essential for unravelling the secrets of the universe, abandoning causal notion is only an option at the most fundamental streams of scientific enquiry and causality remains an essential and unavoidable component of human intelligence.

Humans do not possess or require complete knowledge of the universe. We, as humans make simplifications and assumptions that accommodate our ignorance and allow us to make decisions. These assumptions and simplifications necessitate taking a point of view. The viewpoint taken varies depending on the information available, our perception of salience and our requirements. This viewpoint taken also creates asymmetrical relationships between salient aspects. Certain asymmetrical relationships that result from these simplified viewpoints are causal relationships.

Causal relationships provide a way to understand and interact with an environment under epistemological uncertainty. Modelling the world in a way that fosters causal relationships is very useful. Causal relationships allow humans to learn from their observations and make predictions regarding the consequences of their actions. There are differences between how cultures form and use causal relationships however, the use of causality is consistent and is common to the human condition.

Humans are generally good at ascribing causal relationships in a way that is of some benefit to themselves. This is an evolutionary trait as the better causal reasoners were the ones who more likely to make profitable decisions.

In fact, there is a substantial body of research suggesting that humans innately invoke a form of causal reasoning. Gobnik and Sobel (2000) found that infants as young as eight months are able to reason about causal events. There is also evidence to suggest that causality is the primary tool that allows us to make sense of the world (Cheng, 1997).

If humans are not instinctive causal reasoners, then causality is most likely a universally learnt habit of mind. Causality forms an enormous part of how we talk (Sanders and Sweetser, 2009) and causal relationships are the primary way we choose to encode and transfer information.

It is worth noting that the causal inferences themselves do not necessarily reflect an understanding of the physical mechanisms that underpin these inferences. This does not mean that the inference is not useful. Causal relationships reflecting the purpose and accommodating available information are often more useful than inferences that aim solely to reflect truth or capture physical mechanisms.

For example, in the maritime industry the idea of a ‘pivot point’ is commonly utilised by pilots during ship manoeuvring. The ‘pivot point’ is an imaginary point along the vessel on which a vessel is said to ‘pivot’ during a turn. The term is referenced by many shiphandling textbooks (e.g. Clark, 2005) and provides a powerful mental image of how a ship will behave during a turn which can also be used to assist the development of a causal model for a vessel during manoeuvring. In contrast, hydrodynamicists model a vessel manoeuvring by decomposing the various forces acting on the vessel. These forces can be used in equations that are able to predict the manoeuvring characteristics of a vessel.

Both the ‘pivot point’ and ‘forces’ methods allow the user a predictive power and an ability to understand the consequences of decisions; the approaches differ because the users view the system from a different perspective and with a different purpose. The pilot and the hydrodynamicist have access to different information and need to make different decisions under a different set of parameters. Both methods of decomposition are useful and are tailored to the needs of the user and decisions they make, despite neither providing a ‘complete’ description of the vessel manoeuvring.

Causality's importance to our understanding of the universe, its subjectivity and inscrutability have made causality the topic of a significant amount of debate especially regarding the more fundamental questions, such as '*what is causality?* and '*how should causality be used?'*. Below three statements regarding causality are considered related to the topic as defined in this chapter.

1) *"Causality only survives because it is erroneously believed to do no harm"*, Bertrand Russell (Russell, 1912).

   As a cornerstone of human intelligence, the survival of causality is unavoidable and necessary. Causality is a technique for interacting and making decisions under epistemological uncertainty, which own its own does neither harm nor good. However, particular causal frameworks or poor causal reasoning may cause harm.
2) '*how' should precede the 'why*', central premise of Discourses by Galileo Galilei (Galilei, 1946).

   Or to paraphrase, it is necessary to develop a description of how something behaves before making any explanatory efforts. This approach to scientific enquiry now serves as a platform for scientific reasoning despite not representing how humans actually think and learn. This is due to the importance of avoiding bias in scientific enquiry. When we think however, the 'why' is not divorced from the 'how' and our causal or explanatory frameworks are the drivers for collecting and processing useful information. One tool that allows us to direct inquiry is the counterfactual, this is discussed in Section 2.3.
3) *"We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances"*, Isaac Newton (Westfall and Devons, 1981).

   This is the first of Newton's rules of reasoning. Causality is a way of extracting knowledge from our simplified perspectives. That these perspectives are simplified means we can never obtain a 'true cause'. The term 'sufficient' can be considered to imply the ability to fulfil a purpose, given the available information. The sufficiency of a cause is therefore relative. The 'pivot point' is sufficient for the pilot manoeuvring a vessel however it is not sufficient for the hydrodynamicist to optimise the design of a vessel, and vice versa.

2.3. Counterfactuals

A counterfactual statement is conditional and contains subjunctive clauses that are contrary to fact. Take the following statement from the Formal investigation following the Herald of Free Disaster:

‘this disaster *could have* been avoided if the Chief Officer *had* waited on G deck another three minutes’ (Department of Transport, 1987).

The subjective clauses are contrary to two known facts. Firstly, the Chief Officer *did not* wait the additional three minutes on G deck and the disaster *was not* avoided.

Counterfactual statements are asymmetrical and cannot be reduced to conditional statements of probability, which are symmetrical. To illustrate this, consider that the statement above, it does not imply that.

‘If the disaster *could have* been avoided the Chief Officer *would have* waited on G deck another three minutes’.

There is a strong connection between counterfactual statements and our usual understanding of a cause. This has led to definitions of causality based on counterfactual statement. The most well-known example is from David Hume (1975). This notion of counterfactuals as a tool to reason about alternative realities reached maturity with Lewis’s possible world semantics (Lewis, 1986).

Counterfactuals are extremely important to the way humans reason and learn. It has been postulated that counterfactuals are a signature of the human mental model (Byrne, 2016). Counterfactual statements are also embedded in the way we talk both formally and informally (Kratzer, 2012).

Because of their connection with the common interpretation of a cause, counterfactuals are used as the principal test for determining causation in law (Section 2.7.1). Subsequently, the counterfactual approach is often associated with assigning blame. The use of counterfactuals is not limited to assessing the causal impact of negligent acts. By varying the selection of salient information, the counterfactuals approach can be used to understand and reason in any system.

Counterfactuals are an important tool for learning. Through an exploration of alternate realities, we can extrapolate and learn from contexts beyond those that have happened. This allows us to apply past knowledge to new situations and to develop and consolidate causal models.

With his causal calculus, Pearl defined counterfactuals through causality rather than causality through counterfactuals. This approach suggests that causality is a broader category than counterfactuals and that the common definition of a cause is not enough to grasp causality in its entirety (Pearl, 2009).

2.4. Causality as a Map

Causal models are similar, though more generalised versions of the maps cartographers create to model the Earth’s surface. Both causality and maps represent a simplified perspective and both allow prediction, learning and interaction. This section illustrates the need for causal frameworks to suit the purpose for which they are used and the information available by utilising examples taken from cartography.

The scale and complexity of the Earth mean that our maps are unable to depict everything with perfect resolution. In any case, such a map would not be practical or efficient. Imagine trying to map the location of every grain of sand in the world. Such a map would take lifetimes to make, and upon finishing the map the cartographer would find that many grains of sand had moved since they were mapped. An important element of making both maps and causal networks is knowing what information is important and what information can be omitted.

A special instance of lost information always occurs when mapping the surface of the Earth to a flat 2-dimensional sheet. This is because it is impossible to map the surface of a sphere to a two dimensional plane without distortion. This was proved by Gauss in his Theorema Egregium (Snyder, 1987) and subsequently all world maps feature some degree of spatial distortion. By choosing different reference frames the distortion can be controlled. The various frames of reference used to generate maps are called projections.

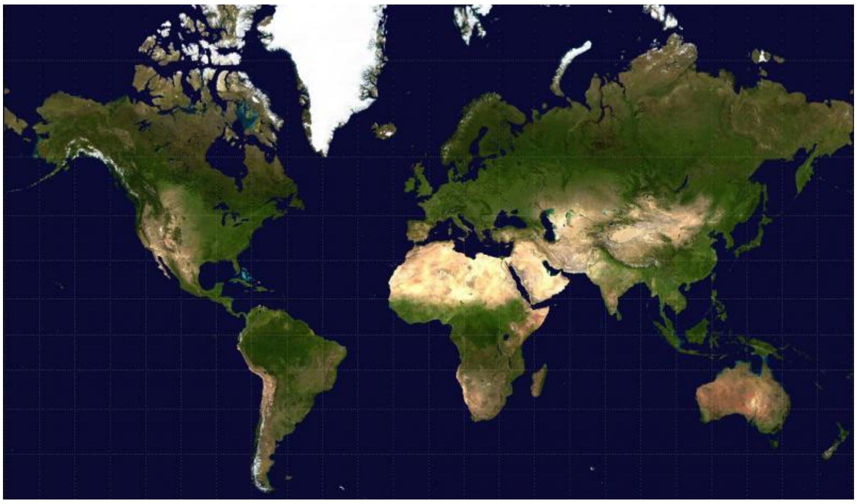

Figure 2-1 A modern map using Mercator's projection incorporating satellite imagery (2009)

There is an infinite number of possible projections, and there are hundreds if not thousands of projections commonly used in cartography. It is the job of the cartographer to decide which projection is appropriate for a given map. This decision is typically based on the maps purpose i.e. what the map shows and what the map will be used for. This purpose directs which properties should be conserved, which can be distorted and which can be omitted.

The most recognisable projection in cartography is Mercator’s projection (Figure 2-1). The projection was first proposed by Gerardus Mercator and was originally intended for marine navigation (Monmonier, 2010). Mercator described his original map as a "new and augmented description of Earth corrected for the use of sailors". The reason the map is “corrected for the use of sailors” is because Mercator’s projection is conformal. This property allows the map to be used in conjunction with a compass to determine a particular course.

A prerequisite to determining an appropriate course is the ability to determine one’s current position. The introduction of Mercator’s projection predated its widespread use because navigators had no means to determine their exact position. Latitude could be determined with reasonable accuracy from the sun and the stars; however it was another 200 years before the longitudinal problem was solved by more accurate sextants and marine chronometers. Collectively, the compass, chronometer, sextant and Mercator’s projection greatly improved navigation and accelerated the Age of Discovery. The chronometer and sextant gave context-specific information which could be fed into the map and used to make decisions regarding course.

A globe overcomes the ‘flat earth’ however other information is still lost or simplified. A globe is therefore just another symbolic representation which evokes simplification. While it solves the map’s ‘flat Earth’ problem it is in fact less useful for marine navigation. This is similar to a pilot’s use of the ‘pivot point’ described in Section 2.2. The pivot point is less accurate than the equations of forces used in hydrodynamics however these equations do not allow the pilot to quickly and accurately make decision regarding vessel manoeuvring.

Mercator’s map highlights two aspects that are important when developing causal models:

Firstly, causal models must be tailored to suit their purpose. This purpose dictates which information is salient and should be conserved. In the case of Mercator’s map, the purpose was marine navigation and local angles were considered important to conserve. A causal model that is useful for one purpose is not necessarily useful for all purposes. For example, Mercator’s projection has been widely repurposed and is now one of the most used projections for wall maps. Geographers have expressed concerns regarding this repurpose because, although local angles are conserved, areas are not. Mercator's projection depicts landmasses close to the poles (such as Greenland, Northern Europe or Canada) much larger than landmasses close to the equator (such as Africa or Indonesia). Some have suggested that the widespread adoption of Mercator's map is testament to a colonialist's viewpoint that promotes, enlarges and centralises Northern Europe, and thus serves a purpose of sorts. I think it more likely that the world maps originally developed for navigation, such as Mercator's projection, were simply repurposed without considering differences in requirements. Nevertheless, the use of Mercator's projection on wall maps in schools has led to a distorted world view by children around the globe. A similarly misguided repurposing of a causal model is discussed in Chapter 3 which focusses on the use of causality in safety analysis.

Secondly, in addition to satisfying a purpose, the usefulness of a causal model is determined by its ability to interact with available information. Had it not been for the compass, sextant and marine chronometer, Mercator's Projection would have been only marginally more useful for the purpose of navigation than any other projection. If a different set of navigational instruments were used during the Age of Discovery, an equally different map projection may have evolved, presumably one that was better able to incorporate the information provided by these instruments.

A final parallel between maps and causal models is that, alone, one map is rarely sufficient to fulfil a purpose. During the Age of Discovery ships kept many charts. While Mercator's map was suitable for navigating the high seas, it was less useful for manoeuvring around harbours, which required larger scale maps incorporating additional variables like bathymetry and navigational hazards. Likewise, in order to navigate through life, people create and develop a vast array of causal models that can be exchanged and combined as a situation dictates, this is one of the key aspects of human intelligence.

2.5. Componentisation and Emergence

Componentisation involves breaking down and simplifying real world systems into smaller, more tangible components for analytical purposes. Just as there are infinite map projections there are infinite schemes of decomposition to develop causal relationships. Typically, systems get componentised into features that that are able to be monitored or controlled. It is common in many fields to decompose systems into physical components i.e. into components that are obvious and can be divided in space. Possessing the ability to monitor or control components does not automatically provide a method of componentisation that is capable of fulfilling a required purpose. Hence, not all methods of componentisation are useful, and no method is universally useful. Componentisation is something performed naturally by humans and the challenge is to find a scheme that generates useful outcomes.

Emergence is a phenomenon whereby larger entities exhibit properties that cannot be explained by the smaller/simpler entities. In other words, emergence occurs when a causal relationship cannot be found for a particular method of decomposition. Examples of phenomena described as emergent include:

- The complex structures formed by schools of fish or flocks of birds. These formations cannot be predicted by the biological and behaviour traits of each individual fish or bird.
- Consciousness, which is often described as an emergent property of neurons firing in the brain (Eccles, 1994).
- Conway's Game of Life in which complex patterns emerge from a very simple set of known laws (Gardner, 1970). This is an example of pseudo-emergence or weak emergence as the known laws make it is possible to predict the patterns that develop however, the intangible quality of the patterns that develop is a good illustration of the relativity of emergence.

Regularities of where emergent phenomena are most commonly cited include situations where:

1. There is a seemingly unequivocal way to decompose the system e.g. decomposing a school of fish into the individual fish of which it is composed.

2. Interactions between components do not easily lend themselves to asymmetric relationships. This could be because the relationships are unstable and dynamic or because there is a feedback loop. Feedback loops can often be the cause of paradoxes as they are a barrier to making logical causal inference. Feedback loops are similar to the concept of a 'strange loop' (Hofstadter, 1980).

It is becoming increasingly common to use emergence itself as an explanation for a given phenomenon. As an explanation, the usefulness of concept of emergence is limited. It does not provide any predictive ability or any ability to understand the effect of interventions. In addition, labelling a phenomenon as emergent stifles further enquiry.

If taken as a description rather than an explanation emergence can be useful, as long as assumptions regarding the method of decomposition are noted. An emergent phenomenon may indicate that the method of decomposition is insufficient for its purpose or for the knowledge available. Emergence, therefore should be viewed as a catalyst, a beginning point, to either acquire new information or adopt a different method of decomposition. Emergence should not be a final resting point for the explanation of phenomena or as a sign that there are no causal explanations. There may or may not be but with infinitely more ways to decompose the system stopping after the most obvious is not evidence of the latter.

2.6. A Definition and Taxonomy of Causality

A significant amount of research has been devoted to establishing a definitive taxonomy of causes. In addition to Hume's attempts to define causality with counterfactuals (Section 2.3) these attempts have seen causes categorised as strong or weak (Miller and Johnson-Laird, 1976); necessary, sufficient or contributory (Wagenaar and Groenewag, 1987); general or singular; a process or a pseudo process (Russell, 1948). These taxonomies may be useful but are essentially arbitrary as causality is dependent on the method of decomposition. The ways to decompose and subsequently relate aspects to one another are infinite. As a consequence, an exception can generally be found to any taxonomy of causality. Most existing taxonomies try to reflect and understand causality as it is used in general discourse. However, causality is used with such diversity that it would be almost impossible to develop a taxonomy categorising just the causality that humans utilise to communicate..

A complete picture of a causality is therefore difficult without painting very broad brush strokes. A general and encompassing definition of a causal relationship is offered below. This definition has been used as the foundation for the causal safety analysis methodology developed in Chapter 4.

A causal relationship between two variables:

Variable A is causally relevant to variable B, if the probability distribution of variable B is dependent upon direct manipulations to the probability distribution of variable A.

The definition has been developed by considering the dependence of the states of a variable under hypothetical manipulations of another variable. The approach is similar to that adopted by Judea Pearl (2009) and is based upon the ideas underpinning causal networks (Section 2.10).

Defining a causal relationship on the effect of manipulation of one variable upon another is asymmetrical and accords with human intuitions regarding causality. For example, the variable *seastate* is causally relevant to the variable *seasickness*, because if we were able to manipulate the *seastate* the rate of seasickness would be affected. In contrast, the variable *seasickness* is not causally relevant to the variable *seastate*, because manipulating the rate of *seasickness* does not affect the *seastate*. This definition is no accident. Understanding effects under intervention forms the essence of decision making and is why causality is so central to human intelligence.

A point of difference between Pearl's view of causality and the definition above is that the choice of what to model is not focussed toward specific values or states of variables; rather, upon the variables themselves. This is similar to the structural approach to causality advocated by Simon and Rescher (1966).

The definition of a causal relationship differs, slightly, from the common use of causality in normal discourse. It is more normal to use causal relationships to relate the states of salient variables rather than to relate the variables themselves. For example, it is more common to say a vessels *poor* stability caused it to *capsize* rather than the *stability of the vessel* is causally relevant to its *angle of inclination*. This approach to causality, based on the relationship between variables, has been adopted for two reasons:

1. Relating variables, rather than the states, creates a model that can be used as an oracle to assess the effect of interventions. This allows inquiries under all conditions that match the granularity of information available.
2. The approach is more compatible with the principles underpinning the modern analysis of complex systems and creates a solid platform for the development of the safety methodology detailed in Chapter 4.

The causal relationship is defined above probabilistically. This also differs from the common use of causality and the use of causality in fields like law and engineering (see Section 2.7) all of which connote a degree of determinism. The case for defining causal relationships probabilistically is given in Section 2.9.

Unlike the examples of causal taxonomies, the definition provided says nothing of the nature of the variables or the relationship between them. These are dependent upon the purpose for developing the model and the information available.

2.7. Accounts of Causality

The previous sections have stressed the relativity and subjectivity of the use of causality. Despite this, many fields have unwritten guidelines pertaining to the appropriate use of causality. These approaches achieve a degree of uniformity in the causal taxonomy of a field. This uniformity is only possible if a field achieves a degree of consistency in both the purpose of use and access to information. A summary of the general use of causality in various fields is given in Table 2-1.

Table 2-1 A summary of causality used in various fields

Field	**Objective**	**Component**	**States**	**Relationships**	**Salient**
Natural Science	Predictive	Everything	None	None	Everything
Other Science	Predictive	Variables	Probabilistic	Deterministic	Correlations
Law	Restorative	Acts	Deterministic	Deterministic	Negligent acts
Engineering	Pred./Rest.	Physical	Prob. (*P*.)/Det (*R*.)	Deterministic	Malfunctions

In fields of science, such as psychology and biology, the deduction of causal relationships is highly valued. Despite causal relationships being coveted in these sciences they are also treated with skepticism and reluctance and there are strict guidelines governing the conditions that these relationships can be inferred. A primary reason for this is that causal claims in research may cause a significant impact to high level policy making. In no other field are the standards for deducing a causal relationship more stringent or rigid. It is worth noting that these standards do not apply to researchers developing research proposals or discussing research informally.

Deterministic causal relationships are evoked in both law and engineering. Both approaches consider the salient information to be that which differs from an accepted norm. Despite these similarities, the two fields use causality for different purposes. In law, causality is used to determine 'blameworthiness' and liability. Engineers use causality to improve the reliability, functionality and productivity of complicated technological systems.

The following subsections explore the use of causality in two fields; law and engineering. Both these fields have been heavily influential to the current causal approach used in safety analysis, discussed in Chapter 3.

2.7.1. A Legal Account

Law implies a degree of determinism, and so it is with legal applications of causality. Initially, causality had no formal purpose but to assign blame or credit. All events could be considered to be caused by humans, animals or Gods. This simplistic idea of causality laid the foundations for modern laws.

408. Whatever may be damaged in a boat by the fault of the boatmen, that shall be made good by the boatmen collectively, (each paying) his share…. 409. In the case of (an accident) caused by (the will of) the gods, no fine can be (inflicted on them). Laws of Manu, Translated from the original text circa 500BC (Doniger, 1991)

This example shows that more than 2,500 years ago, deterministic causality was entrenched in law and its primary use was to apportion blame. The purpose of law has remained largely unchanged and subsequently, there has been little change in the approach to causal attribution. The rules for assigning blame and the exceptions that exonerate one from blame have simply become more numerous and complicated.

This notion of causality is straightforward but problematic. A deterministic approach to causality, combined with incomplete knowledge, means there is unconsidered context specific information. The result is that determining causation is generally left to common sense (Panel and Ipp, 2002). It is the role of judges to process this uncertainty using their own causal model, and the precedents set by the causal models of judges past.

Below is a brief criterion for determination of liability for an act of negligence in Australia (Fleming, 1987):

1. *Negligence:* An act must have been committed that breached a duty of care.
2. *Causation-in-fact:* The act of negligence must have *caused* the damage being claimed by the defendant. The usual test for causation-in-fact is the ‘but-for’ test. This is a counterfactual query regarding whether the damage would have occurred ‘but for’ the breach of duty of care. It is a deterministic query that rarely outputs a deterministic answer.
3. *Causation-in-law:* The act of negligence must not be too ‘remote’ from the damages; nor should there be any intervening act that breaks the chain of causation. This is also known as the foreseeability or the common sense cause. Presumably because, like causation-in-fact, it is left to common sense. Interestingly, the onus of proof for any aspect relating to causation in cases of negligence is on the plaintiff.

The idea of a causal chain is commonly accepted in law. The causal chain is a singular, linear and deterministic path of events, that is initiated by improper act. The salient aspects of the causal models used in law are the actions that are considered violations of a norm e.g. 'the breach in duty of care' or 'the intervening act that breaks the causal chain'. The focus on salient acts reflect the legal purpose, to determine 'blameworthiness'.

The legal approach to causality has significant historical ties with accident investigations. Until recently, an accident investigation needed to concurrently develop recommendations designed to improved safety while undertaking judicial proceedings (White, 1993). Lawyers played a substantial role in the development of the salient aspects of the causal models used in accident investigations.

The *Wagon Mount (No. 1)* is an example of the legal causal framework. In 1951 a crude oil tanker, *The Wagon Mound* was docked in Sydney harbour. The crew allowed bunker oil to spill into the water. Burning metal from welders working on the nearby timber dock caused the oil to ignite subsequently leading to substantial fire damage to the dock and several nearby vessels. The dock sought compensatory damages from the owners of *The Wagon Mount* for negligence. The actions of the crew were found to be negligent and there was found to be a direct causal chain between the crew's actions and the consequences. Despite this It was ultimately determined that the negligent act was too remote from the consequences and as such was not reasonably foreseeable. The owners of The Wagon Mount were not held liable for damages caused by the crew's actions that were not reasonably foreseeable. In this causal framework the salient aspects are actions and consequences and causal chains are used to determine blameworthiness.

A single causal model applied for two often conflicting purposes usually means sacrificing the quality of useful outcomes. While the two purposes of an accident investigation have now been separated, the causal assumptions used in law are still prevalent in modern accident investigations. Modelling actions considered improper is still a common starting point for accident investigations, and 'human error' is a commonly cited cause for many accidents. Using improper actions as the focus of investigations is much more useful for attributing blame than it is for improving safety.

2.7.2. An Engineering Account

When engineers began designing complicated, multistage systems, it proved extremely useful to utilise formal methods of decomposition. Decomposing systems into components allowed the functionality of each to be analysed separately. By applying causal relationships to the inanimate components of multistage systems, engineers were among the first to draw a distinction between cause and blame.

Decomposition provided economic benefits as well because, when a system failed only a single component required replacement. This approach also provided the building blocks for new systems, which could be developed by adding or rearranging components. This is still the fundamental principal that guides system design and analysis today. Faulty components can be replaced with better ones and functionality can be improved by altering or adding components or combining them with components from other systems. This approach aligns with a reductionist view of the world, whereby structures can be decomposed and understood from more basic building blocks which, in turn can be treated independently. As with the approach adopted in law the salient information considered by engineers is the component that function improperly.

One of the assumptions that allows system components to be analysed independently is that the interactions between component states are known and obey fixed laws. The laws of component interactions are typically causal and convey determinism.

Unlike their counterparts in science, engineers have never been reluctant to infer causal relationships. Following the statistical revolution, a wealth of data was generated relating to the failure rates of individual components. When combined with the qualitative causal relationships between component states, engineers are able to predict system outcomes in context-specific situations. More importantly, this approach allowed engineers to understand the effect of hypothetical system interventions. Such an understanding would not be possible using the symmetrical correlatory dogmas of the statistics. There are generally two approaches to the causality used in engineering:

- ‘Same level causality’ where the state or output of one component affects or initiates the next component in the chain as though the system could be viewed as if it was a line of dominos. This approach to causality is commonly applied to the design and control of multistage systems such as a production line (Figure 2-2) or the drivetrain of a motor vehicle.

- In bottom-up causality the more fundamental building blocks combine to affect a higher level of a predefined or intuitive hierarchical system. Sub-components combine to form components at a higher level of the hierarchy. Computer programs use this type of causality to build functionality. The most basic commands of a programming language are combined in various ways to generate more complicated and sophisticated functionality. These programs are then combined with other similar programs to further increase functionality. This approach has allowed systems in many fields to develop at an exponential rate.

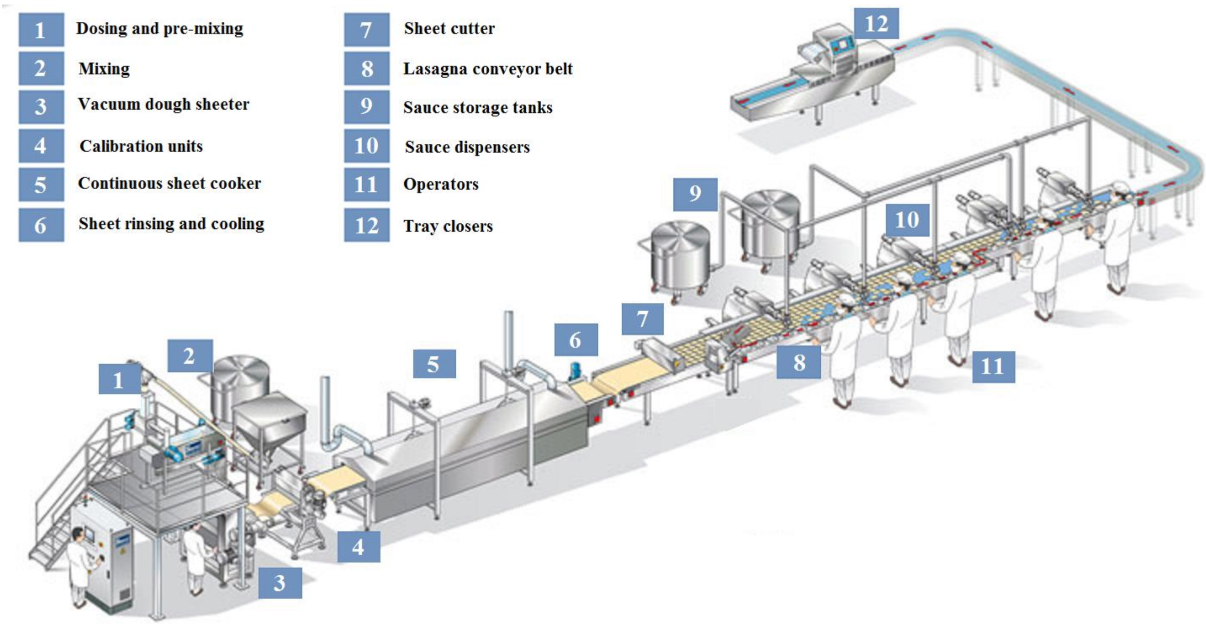

Figure 2-2 A lasagna production line showing independently functioning and sequential components. Note that the sheets of pasta must be applied manually (adapted from www.storci.com).

It is not by chance that the components of engineering systems can be treated independently and yield useful outcomes. The deterministic causal relationships between components were designed rather than discovered. This is partly because the choice of delineation of components aligned with the delineation of functions performed by the system (e.g. Figure 2-2, each component completes a single function with little or no overlap). Many systems were therefore designed with a degree of independence to aid analysis. It is also partly because the ‘find cause, fix cause’ approach to improving system reliability influenced the evolution of system designs. Where a system proved inadequate because the causal relationships did not match the prescribed deterministic assumptions, the component would be improved such that the violation no longer proved problematic. Thus, the deterministic causal assumptions of independent components have a feedback effect on the system design. Through a period of stabilisation, many systems have evolved to reflect the assumptions from which they were designed and assessed.

The goal and purpose for adopting causal relationships to assess engineering systems is clear and the approach led to huge advances in the sophistication and reliability of technological systems during the 20th century. The practical advantages of inferring causal relationships to the components of complicated technological systems outweighed the need to conduct rigorous appraisal of their validity.

Unsurprisingly, the engineering approach to causality has heavily influenced the methodologies used in safety analysis. Deterministic causal relationships between components are utilised in the vast majority of safety analysis methodologies. There is a strong connection between the fields of reliability engineering and safety analysis and the models used to assess system reliability have frequently been repurposed to assess safety (see for example Cui el al., 2007). Additionally, the responsible party for assessing the safety of a complex socio-technical system is often an engineer who is trained in the engineering approach to system analysis.

2.8. Uncertainty and Probability

Probability is a measure of the likelihood that an event will occur (Walpole and Myers, 1993). In general, there are two approaches to probability: The frequentist approach and the Bayesian approach. That we are dealing with likelihoods rather than sureties means that probabilities are closely related to uncertainty. Probability provides a language for uncertainty that is both expressive and widely recognised.

Both the frequentist and Bayesian approaches to probability utilise the language of probability but the two approaches differ in their taxonomy of uncertainty and the use of probability based on these taxonomies.

The frequentist approach adopts a taxonomy that distinguishes between aleatory, that which is the irreducible through repeat trial; and epistemic, that which is the result of incomplete information and can be reduced through repeat trials. Probabilities are only used to express aleatory uncertainty and can only be applied after the epistemic uncertainty has been reduced to an acceptable level. The goal of the frequentist is to *determine* probabilities by conducting a sufficiently large number of trials to reduce or eliminate epistemic uncertainty. The frequency of each outcome may then be expressed as a probability, hence the term frequentist.

To the frequentist, the aleatory uncertainty and the probabilities deduced are not really expressions of uncertainty at all. To the frequentist, probabilities exist and can be found and are expressions of truth rather than doubt.

When presented with an unknown six-sided dice the frequentist would initially decline to provide a probability of a given outcome relating to the rolling of the dice, until the dice had undergone a sufficient number of repeat trials to reduce epistemic uncertainty and determine the probability of the outcome. If the dice proved to be fair, the frequentist would assign a probability of *1/6* for each number. The frequentist approach to probability is the prevailing view in mainstream science.

The Bayesian approach to uncertainty makes no distinction between epistemic and aleatory uncertainty. Rather, all uncertainty is epistemic and considered the product of incomplete knowledge. Probabilities, under a Bayesian approach, are a measure of the *belief* that an event will occur. Probabilities can be applied to any situation regardless of whether a large number of repeat trials have been conducted and are expressions of doubt rather than something to be found. Because they are beliefs rather than statements of truth, probabilities shift depending on the evidence available.

Bayes theorem provides a mechanism for adjusting beliefs based on new evidence. Bayes' theorem expresses the relationship between the belief in a hypothesis (H) before evidence (E) and the belief in a hypothesis after evidence (Equation 1).

$$P(H|E) = \frac{P(E|H)}{P(E)} P(H) \tag{1}$$

Bayes theorem is also used from a frequentist approach but as a mechanism to evaluate compound probabilities. The probabilities themselves are fixed.

When presented with the same six-sided dice as the frequentist and asked to provide a probability for rolling a particular number, the Bayesian, having no reason to favour one outcome over another would assign a probability of *1/6* for each event (Jaynes, 1957). By providing these probabilities the Bayesian is not expressing any belief that the dice is fair and without any information the Bayesian would have no reason to believe a dice is fair or not fair and would believe both possibilities equal.

After witnessing the frequentist's trials, the Bayesian's belief would alter to accommodate the new evidence. Without any other evidence the probabilities would closely match those of the frequentist. However, these probabilities remain expressions of belief.

After repeat trails, if the dice proved to be fair, the Bayesian’s belief in the outcome would remain unchanged. The frequentist is satisfied that the probability of each outcome has been deduced and is content with the outcome of the study. The Bayesian has not gained any information regarding the outcome of the dice, however the Bayesian belief that the dice is fair would have increased significantly. The Bayesian would look for other variables that may be more useful in predicting and interacting with the outcome of the dice roll.

The Bayesian approach mirrors the way humans think more than the frequentist approach. We rarely have the benefit of long-range statistics to help us make decisions. The Bayesian approach to probability allows us to make decisions under epistemic uncertainty. Humans are remarkably good at making decisions under uncertainty and the way we alter our belief to accommodate new evidence closely matches Bayes theorem. The ‘Bayesian brain’ hypothesis is the idea that empirical evidence is stored in the human mind as a probability distribution (Jaynes, 1988).

However, the importance of heuristics on human judgement is well known (Kahneman & Tversky, 1999) and it is the contention of Pearl (2009) that humans store knowledge using causal laws rather than encode in probabilistic distributions. Humans are generally oblivious to rates and proportions which are transitory and constantly search for causal relations which are invariant. If humans were governed by the law of proportions rather the causal laws, then statistical paradoxes such as Simpson’s paradox would elicit no surprise and would have never garnered the attention it has.

Irrespective of the primary method of accommodating information, the Bayesian approach to probability aligns with our understanding of how humans deal with uncertainty, including how we come to our beliefs, how we change our minds and how we evaluate counterfactuals.

2.9. Causality and Probability

To define causality using probability seems at odds with how causality is generally applied and with how causality is applied in fields such as law and engineering (Section 2.7). However, as discussed in Section 2.2 causality is the result of taking a viewpoint to accommodate incomplete knowledge. Uncertainty is therefore an unavoidable consequence of all causal models and, as discussed in Section 2.8 the Bayesian approach to probability is a useful language for treating uncertainty. There are several other reasons for stressing a probabilistic analysis of causality.

1. Causality is not always used with the deterministic strength adopted in law and engineering. The causal utterances we make are plagued with uncertainty and doubt e.g. The phrase ‘smoking causes cancer’, does not imply that everyone who smokes will get cancer but that the act of smoking makes cancer more likely. Any theory of causality must attempt to accommodate such utterances and thus distinguish shades of likelihood.

Investigators are not only concerned with the presence and absence of causal connections but also with the strength of these connections and methods for inferring these connections from noisy observations. The language of probability provides the capability to cope with noisy observation and express their strength.

2. Causal utterances, even the ones connoting determinism, are riddled with exceptions and probability theory is equipped to accommodate these.

Our decompositions, based on our perceptions of salience, are necessarily simplified and incomplete. The consequence of this is that the relationships we form are not deterministic and that exogenous information can always generate exceptions to our causal laws. Probability theory offers a highly developed and systematic language for dealing with uncertainty and allows the salient aspects and the causal relations between these aspects to be developed at a level which matches the granularity of normal discourse, without requiring assumptions of determinism.

3. Adopting a probabilistic approach to causality in safety analysis is driven by the hypothesis that humans discover causal relationships from empirical evidence, this idea was first suggested by Hume (1975). Incorporating a Bayesian probabilistic approach to developing causal models offers the potential to extract the experience of operators and more importantly the ability to update and refine these models as new information becomes available.

A Bayesian approach to probability accommodates information and evidence that may be contradictory, incomplete or uncertain. Such scope would not be possible using a deterministic approach to causality.

4. Probability theory is currently the language used by most fields to express uncertainty. Although other schemes exist e.g. Dempster-Shafer Theory (Shafer 1976) they are not as developed, intuitive or universal as probability theory.

In most fields of science probability theory has been divorced from any notion of causality. The key players of the statistical revolution during the first half of the 20^{th} century were largely responsible for propagating this separation.

In fact, causality is not in the standard vocabulary of probability. Cause and effect cannot be distinguished in based on correlation alone because the relationship is symmetrical. The fallacy of inferring causation based simply on correlation is well known. To safeguard against this the statistical revolution raised the standard for inferring causal relationships in science. Today, Fisher's randomised experiment is the only universally accepted method for inferring causal relationships (Pearl, 2009). The approach is based on randomised manipulations of a variable in a controlled environment to determine its effect on another measured variable.

However, even without the benefit of rigorous randomised experiments humans are able to infer causal relationships. Scientists can often predict the results of an experiment under a completely different set of conditions. These predictions require us to envisage what the world would be like after various hypothetical changes and so invoke counterfactual inferences. Such inferences cannot be formalised using the standard languages of logic, Boolean algebra or probability. However, the notion of causality is ever present in the language scientists use to discuss theory and direct investigation.

Karl Pearson, a key member of the statistical revolution, stated that correlation formed a broader category than causation and that the descriptions of associations were all that was necessary to understand the world (Reiss, 2012). This idea has heavily influenced how science is conducted to the extent that it is rare to find causal relationships explicitly stated in scientific papers and rarer still to find significant discussion of causality in statistical textbooks.

Finding correlation only provides some of the information necessary, to make decisions in an uncertain domain, causal relationships must be invoked. Without asymmetrical causal relationships there is no way of understanding behavior under intervention. In many sciences the goal is not simply to describe the world but also to understand the effect of policy changes. Causality remains critical in these fields as an oracle for interventions.

Probabilistic causality is a branch of causality that attempts to explain causal relationships using the language of probability. The formal program of probabilistic causality owes its inception to Reichenbach (1956) and has been pursued by others, notably Salmon (1984). Significant advances in combining qualitative causal relationships with the language of probability have been made by Pearl (2009) who combined probability theory with graph theory.

Graphs are proving to be an important tool in combining causality and probability. Graphs provide a way to express the relationships that are not easily expressed with the current language of probability and mathematics. Graphical methods now provide a powerful symbolic machinery for deriving the consequences of causal assumptions.

2.10. Causal Networks

As commonly used, a model is an idealised representation of reality that highlights some aspects and ignores others. We create a model when decomposing aspects of the world and relating them to one another, as discussed in Section 2.2.

Models that are useful to us usually involve the interaction of many variables and draw upon many submodels with variables of their own. The number of possible contexts increases exponentially with the number of variables. When there is uncertainty surrounding a variable's state the variable may be modelled with a probability distribution. This results in an n dimensional joint probability distribution across the entire model which quickly becomes unmanageable for all but the simplest systems. In reality however, the state of one variable does not influence the outcome of every other variable in the model and the joint probability distribution may be simplified through assumptions of independence.

Bayesian networks belong to the family of probabilistic graph models which integrate a combination of graph theory and probability theory. Bayesian networks, also called belief networks, knowledge maps or causal networks, utilise graph theory to model the independence assumptions of an uncertain domain.

The Bayesian network consists of a directed acyclic graph (DAG) and a joint probability distribution over a set of random variables (Jensen, 1996). Bayesian networks are used to represent the state of knowledge of an uncertain domain and have been widely applied to model knowledge domains in an extremely diverse range of sectors.

The DAG consists of nodes and arcs. Each node in the DAG represents a random variable that is defined by the possible states it can take. The states of a node can be either continuous or discrete. The directed arcs which connect the nodes give information about dependencies between the variables. The dependencies specified by an arc can be but are not limited to causal or temporal relationships (Pearl, 2009). Although adopting a causal DAG structure will lead to a more efficient network (Pearl, 2014) information can spread in any direction through the network. An example of a Bayesian network is shown in Figure 2-3 with circles representing nodes and arrows representing arcs.

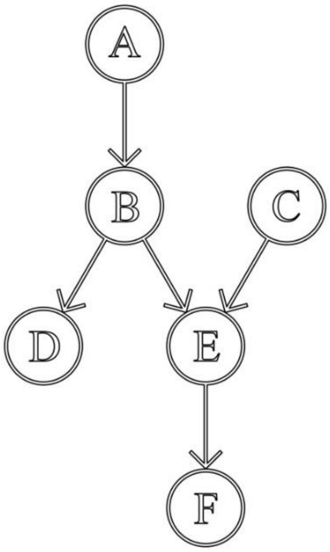

Figure 2-3 An example of a directed acyclic graph consisting of six random variables (A-F)

Encoded in the structure of the DAG are the conditional independencies which allow the joint probability distribution to be condensed through assumptions of independence, these independency assumptions are governed by the rules of d-separation. D-separation allows the joint probability distribution to be given by multiplying the conditional probability distributions of each node (Xi) given the set of the node's direct predecessors (pa) parents as per Equation 2. This assumption of conditional independence usually substantially decreases the number of parameters required to specify the joint probability distribution (Neapolitan, 1990). Additional benefits of Bayesian networks include being able to merge and update evidence from different sources and being able to utilise incomplete, small or uncontrolled information.

$$P(X_1, \dots, X_n) = \prod_i P(X_i | pa_i) \tag{2}$$

The process of building a Bayesian network can be separated into two parts. The structural learning involves shaping the DAG to suitably represent the domain being modelled. The structure of a Bayesian network can be learned either through expert judgement or through available data using automated algorithms. Automatically learning Bayesian network structures is an important topic in artificial intelligence and machine learning (Neapolitan, 2003). The challenges of structuring a Bayesian network are analogous to the challenges of selecting the right projection for a map (refer to Section 2.4).

Parameter learning is the development of the conditional probability distributions of each node given the direct predecessors known from the structure of the Bayesian network. As with structural learning, parameter learning can be expert or data driven and there are many algorithms available for automatically learning parameters (Neapolitan, 2003).

When a Bayesian network is arranged so that the directed arcs are indicative of a causal relationship the network becomes a causal network. A causal model is a triple consisting of the background variables (U), (determined by factors outside the model), endogenous variables (V, determined by factors within the model) and a set of functions (F) that map U to V. Every causal model can be associated with a directed graph. A probabilistic causal model represents the causal model and the probability function over the domain U, P(U). In causal network the structural learning involves mapping the causal relationships between variables while parameter learning involves mapping the strengths of these causal dependencies

Apart from efficiency, there are further advantages to ascribing causal notions to the directed arcs of a Bayesian network.

Firstly, focusing on modelling causal relationships promotes a Bayesian network structure that represents its domain using stable and invariant mechanisms. As discussed in Section 2.5 emergence often follows methods of decomposition that incorporate variables that do not lend themselves to causality. Relationships in non-causal networks may be transient or circular.

Secondly, by arranging the network causally it becomes an oracle for intervention allowing the user to analyse the result of intervention or counterfactuals by undertaking surgery on the network. An example of this can be seen in Figure 2-4 which depicts a surgery undertaken on the network depicted in Figure 2-3. The intervention is occurring on variable B divorcing its dependence on variable A.

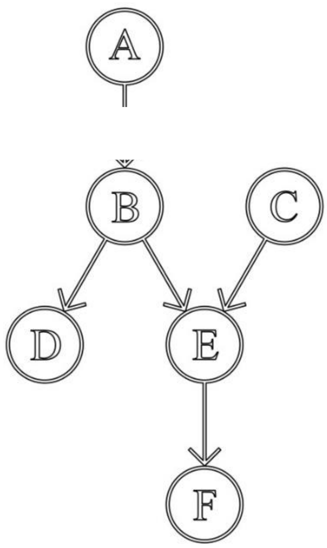

Figure 2-4 A surgery undertaken detached variable B from its parent variable A

2.11. Conclusion

Causal relationships allow us to learn and make decisions despite incomplete information. Causality is used with incredible diversity and is a relative concept. Various fields such as law and engineering have developed guidelines on the appropriate use of causality. These guidelines are tailored to the purpose of the investigation and the information available.

A formal language for expressing causality has proved to be elusive due to a perceived conflict with the prevailing ideas regarding scientific enquiry. However, the centrality of causality to human cognition highlights the value of a formal language and to date the most promising avenue for achieving this has been the combination of probability theory and graph theory.

The Bayesian approach to probability provides a formal language that is able to accommodate epistemic uncertainty. Graph theory is able to capture the information contained in an asymmetric causal relationship. Chapter 3 investigates the application of causality within the field of safety analysis.

Chapter 3 An Exposition of Causality in Safety Analysis

3.1. Introduction

Safety is a concept with which most of us feel we have some familiarity. The ultimate cause for safety is the reduction of harm to people and property. This is the purpose for which all safety analysis is undertaken. Safety is a topic that impacts all of us in a very immediate way and public expectations for safety have increased dramatically over the last half a century. Despite increased importance, the process for improving the safety of a system has remained relatively unchanged. Throughout this period the portion of failures considered ‘technological’ has decreased while the complexity of system has increased exponentially. The combination of these changing boundary conditions makes the effectiveness of the current causal modelling of systematic safety unable to satisfy society’s increased demands for safety.

Recently new ideas are challenging the underlying approach to safety analysis. A new approach, known as Safety-II (Section 3.5), takes a transposed view to the traditional and currently accepted, Safety-I (Section 3.3). The differences are analogous to a different method of decomposition discussed in Chapter 2. Safety-II is closely related to Resilience Engineering (Section 5.2) which promotes a holistic approach to safety analysis.

Just as causality is embedded in the way humans model the world, so is it embedded in the modelling processes of safety analysis. Causality is apparent in all aspects of safety analysis that relate to modelling systems and developing recommendations. All accident investigations and risk assessment methodologies employ a form of system decomposition to make analysis manageable. The relationships between the aspects of these decomposed systems universally invoke a form of causality. The variability of causality used in safety analysis is illustrated in Section 3.2. Section 3.3 investigates the causal framework currently adopted in safety analysis and the methodologies currently used in accident investigation and risk assessments. Section 3.3 also reviews the use of causal networks as tools for safety analysis. Section 3.4 discusses some of the limitations with the causal framework currently applied in safety analysis. Section 3.5 introduces the Safety-II approach for considering safety and discusses the causal implication of adopting this approach. Section 3.6 defends the use of causality in safety analysis by stressing its importance for developing recommendations.

3.2. A Myriad of Causes

As discussed in Chapter 2 causality is used with incredible diversity and complexity. It is perhaps to be expected that causality is used with similar diversity when formalised for use in safety methodologies. Causal analysis following the *Herald of Free Enterprise* disaster illustrates this diversity.

The *Herald of Free Enterprise* was a roll-on, roll-off (RO-RO) ferry that departed the Port of Zeebrugge, in 1987 with her bow door open. Within minutes of departure, water flooded the main compartment and the vessel capsized resulting in the loss 193 lives. A court of marine inquiry was set up to investigate the causes of the casualty (Sheen, 1987). In addition to the causes identified within the inquiry, a plethora of articles have since been published that explore the importance of other causal factors (Dand, 1989, Praetorius et al., 2011). A list of some of these factors is given in Table 3-1. In addition to listing the causes, the Table below attempts to make some distinction between the causes through classification.

Table 3-1 An incomplete list of causes relevant to the *Herald of Free Enterprise* disaster. The causes have been categorised to illustrate the diversity in semantics

ID	Causes	Category	Nature	Generality
1.	*The bow doors were open during departure*	Technological	State	Specific
2.	*Time pressures*	Psychological	Conceptual	General
3.	*Human error*	Human	Conceptual	General
4.	*'Sloppiness' from the body corporate*	Organisational	State	General
5.	*Poor ship management*	Organisational	State	General
6.	*Fatigue*	Psychological	Conceptual	General
7.	*The crew's negligence*	Human	State	General
8.	*Design vulnerabilities*	Technological	State	General
9.	*The lack of a marine superintendent*	Organisational	State	Specific
10.	*Carrying too many passengers*	Organisational	State	Specific
11.	*High staff turnover*	Organisational	State	Specific
12.	*Lack of warning system*	Technological	State	Specific
13.	*Water ingress into the vehicle deck*	Physical	State	Specific
14.	*Poor company culture*	Organisational	State	General
15.	*Loss of transverse stability*	Physical	State	Specific
16.	*The assistant bosun's failure to close the bow door*	Human	Omission	Specific
17.	*The bosun's failure to check the bow door*	Human	Omission	Specific
18.	*The captain departing*	Human	Action	Specific
19.	*Squat effect*	Physical	Conceptual	General
20.	*Free surface effect*	Physical	Conceptual	General

The classification of causes given in Table 3-1 is not intended to be a definitive taxonomy of causality in safety, but rather illustrates the variability of causal vernacular ascribed in safety analyses. It also emphasises the difficulties faced by investigators in amalgamating the causality used in normal discourse into a coherent model.

It is testament to human ability to simultaneously accommodate various causal models that this list does not seem contradictory or inconsistent. However, attempts to pool and map these causes using a single model creates difficulties because of differences in each individual cause's taxonomy and level of resolution. As such, the safety assessors must decide what causes are pertinent to the investigation. Qualitative decisions regarding focus and decomposition scheme have a far greater effect on the outcomes and recommendations of safety analyses than the sophistication of the quantitative methodology implemented.

Despite its importance, relatively little attention has been given to the role of causality in safety analysis and there is limited guidance on the structuring of causal relationships. The majority of mainstream research is focused on advancing the quantitative component of safety methodologies. Qualitative decisions, though inescapable, are often ignored due to their apparent subjectivity. This leaves the safety assessor reliant upon a mix of intuition, tradition and the judgement of experts to develop qualitative aspects of safety models.

3.3. Safety-I: The Prevailing Causal Framework.

There is no universal taxonomy of causality. Despite this, many fields have developed guidelines that govern the usage of causality (See Section 2.7). Differences in the causal frameworks between fields can be significant and generally mirror differences in the purpose for which analysis is being undertaken and the information considered salient.

The field of safety analysis has also developed an unwritten set of rules governing the use of causality in formal systems. In this section the current approach to causality utilised in formal safety analysis is termed Safety-I.

Safety research is a relatively new field of research and is often at the interface of more established research fields with developed and standardised approaches to causality. Safety-I has evolved to be a hybrid of several divergent approaches including science, engineering and law. A detailed account of each causality in each of these fields is given in Section 2.7.

The basic premise of Safety-I is that accidents and incidents will decrease as safety increases, this also serves as a measurable under the Safety-I construct. This premise aligns with most people's belief that one of the fundamental purposes for conducting safety analysis is to eliminate or reduce accidents and incidents that damage the things we value, such as people, property or the environment. Most safety methodologies seek to reduce the potential for accidents and incidents by reducing or eliminating malfunctions of system components. The assumption of the Safety-I approach is that all accidents can be traced to a cause. The causal implications of the Safety-I framework are shown below in Table 3-2.

Table 3-2 A summary of the causal framework underpinning Safety-I

Predictive (e.g. risk assessments)	
Purpose	Reduce accidents that cause harm to people or property. May also serve reliable purposes
Objective	To identify and mitigates components in the system that may fail
Components	Physical components e.g. a mechanical component or a person. Expanded to include more abstract components e.g. organisational culture.
States	Bimodal e.g. fail-safe, function-malfunction.
Relationships	Causal and probabilistic (frequentist approach)
Salient	The components that may behave incorrectly.
Measurable	Assessment of: • *The frequency of things going wrong* • *The consequence of things going wrong* The product of the frequency and consequence is commonly called risk.
Outcomes	Recommendations designed to reduce the frequency of a malfunction or mitigate its effect.

Restorative (e.g. accident investigations)	
Purpose	Investigate an accident that caused harm to people or property. Until recently, judicial purposes also.
Objective	To investigate the causes of an accident to prevent history repeating
Components	Physical components e.g. a mechanical component or a person. Expanded to include more abstract components e.g. organisational culture.
States	Bimodal e.g. fail-safe, function-malfunction.
Relationships	Causal and deterministic
Salient	The components that behaved incorrectly.
Measurable	Assessment of: • *What failed?* • *What was the outcome?*
Outcomes	Recommendations designed to prevent history repeating itself.

Formal Safety-I methodologies were developed primarily between 1965 and 1985 at a time when systems were becoming increasingly complicated. Prior to this safety analysis was conducted informally, although its purpose still matched that described above. Safety analysis was first formalised in fields such as the nuclear industry and the aviation industry. The need for formal analysis was driven by two reasons:

1. The informal system-wide approach was insufficient for analysis of systems at the cutting edge of technological development. These systems were combining components in unprecedented numbers and with unprecedented sophistication.
2. The consequences of accidents in these fields were so appalling that there were substantially increased demands for safety. Such demands could not be satisfied practically or legally with an informal system.

The find-cause, fix-cause dogma that typifies the Safety-I approach proved extremely useful in reducing the rate of technological failures in complicated technological systems. Using decomposition to determine what went wrong is a natural approach that aligns closely with the methods we use to solve problems. This causal approach was particularly suited to eliminating failures of designed technological components and, as these systems were developing, the majority of failures could be traced to a technological cause.

The severe consequences of failure meant that these systems spent significant time in development. This afforded complex systems the time to iteratively eliminate malfunctions. The causal model used in safety analysis was designed to reflect the system. Where discrepancies between the model's assumptions and the system existed, these would be iterated out of the system during the development phase. Therefore, the causal framework became influential in the development of the system itself.

This was useful not only for reducing harm but also for developing and improving technology. The purpose for conducting a safety analysis was aligned with the engineer's goal of improving technological reliability. Thus, improving safety and reliability could be conducted concurrently using the same causal models.

As the technologies used in these industries became increasingly stable the proportion of causes which could be directly attributed to technological failures began to reduce. As a result, the scope of safety analysis expanded beyond the field of engineering to include other components such as human factors and organisational structures. The focus of accident modelling and risk analysis switched from malfunctions caused by physical technological components to malfunctions caused by humans and organisations. In general, the same approach is used to address these malfunctions as is used to address technological malfunctions i.e. Improve the component or remove it.

As with engineering, safety analysis is used to improve safety proactively with risk assessments, and also restoratively with accident investigations. Despite the two fields having distinct and different purposes they share similar methodologies that have developed concurrently. The following subsections briefly detail the methodologies used for safety analysis both restoratively and proactively.

3.3.1. Accident Investigations

The requirement for safety analysis to fulfil varied purposes is most evident when applied restoratively. According to Sklet (2002), an accident investigation may be conducted to fulfil several roles, including to:

1. identify and describe the true course of events (what, where, when)
2. identify the direct and root causes / contributing factors of the accident (why)
3. identify risk reducing measures to prevent future, comparable accidents (learning)
4. investigate and evaluate the basis for potential criminal prosecution (blame)
5. evaluate the question of guilt in order to assess the liability for compensation (pay)

These purposes align with the singular goals of other fields. Role 1 reflects the descriptive view common to the scientific principle of observation. Roles 2 and 3 reflect the engineer's use of causality as a tool to understand and improve a system. Roles 4 and 5 summarise the legal approach to causality (Section 2.7.1) as a means of assigning blame and determining liability.

Until fairly recently formal accident investigations were required to fulfil all of these purposes concurrently (White, 1993). Accident investigations had to establish a description of the events and identify root causes. Simultaneously, the investigation served a formal judicial purpose where the blameworthiness and liability of various parties was determined. Additionally, the final report of an accident investigation will also contain recommendations that usually lead to regulatory or policy changes.

Recently there has been a strong shift toward no-blame accident investigations (Dekker, 2015). These investigations are carried out by an independent authority and sever the link between safety and blame. No-blame safety investigations allow participants to speak freely, while being protected from any legal repercussions (Dolan, 2012).

Accident investigations rely heavily on expert judgement to identify the causes of accidents (Roed-Larsen et al., 2004). Variability in the perceptions of salience often causes inconsistencies in the outcomes of accident investigations. This variability is the result of varying past experiences that precondition the expert into adopting a particular causal model.

Most countries and industries have rules and guidelines that promote a standardised approach to accident investigations e.g. Australia's Transport Safety Investigation Act (2003). Although blame has, for the most part, been formally detached from the objectives of accident investigations, an approach to causality preoccupied with failure and the improper actions of humans persists.

A deterministic view of causality is favored in accident investigations. Systems are decomposed into physical components and investigations revolve around trying to determine which component did not function correctly. Humans are included as another component in safety analysis. The proportion of accidents identified as 'human error' is substantial. Between 1999 and 2006, 96% of investigated aviation accidents in the United States were attributed in large part to the flight crew. In 81% of these cases, human error was the sole reported cause (Dekker, 2010). The identification of a single malfunctioning component is the most common outcome for accident investigations.

Alternatively, single causal chains are used to describe sequential flows of events. This approach is similar to the causal chain of events used in law. Heinrich's domino model of accidents (Figure 3-1) invokes a form of top-down causality where root causes are attributed to higher order and more abstract concepts such as culture and management (Heinrich et al., 1980).

The domino model was the first in a class of models known as sequential accident models. Failure modes and effects analysis (FMEA) and fault trees are two later examples of this type of model. These models are still widely applied to investigate accidents in a wide variety of systems (Kapur and Pecht, 2014).

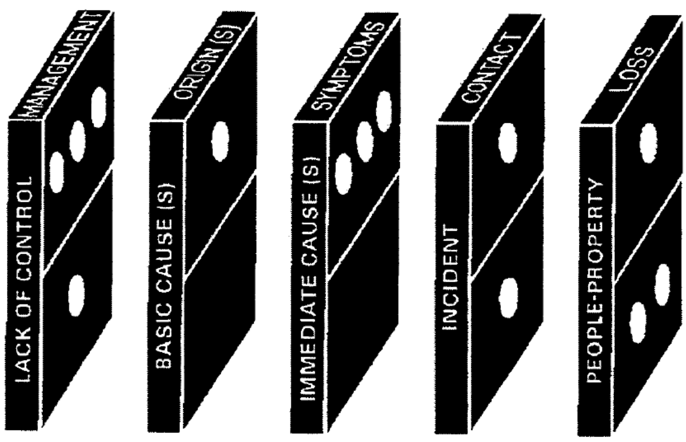

Figure 3-1 Heinrich five-step domino sequence for accidents (Fry, 2000).

Sequential accident models of causation aim to provide a template to direct an appropriate use of causality to generate useful and consistent outcomes during accident investigations. Deterministic, linear and sequential approaches are the most commonly implemented accident causation models.

Traditional accident models, along with the causal frameworks they adopt, contrast research into complex systems, human factors and the modern system theoretical framework (Lundberg et al., 2009).

It was realised by safety researchers that sequential accident models of causation do not address the complexities of modern systems that incorporate complex human and organisational interactions. A wider systematic approach should be taken to accommodate these factors.

There are several accident models that aim to incorporate systematic and complex ideas regarding accident causation. These models promote consideration of a broader range of causal factors and often model a causal network with multiple sequences as opposed to a single causal chain. Considering a range of causal factors helps delineate cause from blame.

Reason's Swiss Cheese Model (1990) is one of the most well-known and widely applied human system accident models. Under Reason's model an accident is attributable to both latent causes (such as poor supervision) and active causes (such as an operator's erroneous decision). This approach requires an acceptance that accidents are not simply the result of an active human error but are in fact the result of a system wide organisational structure.

Layers of Swiss cheese provide a metaphor for the layers of systematic defence against accidents. Holes in the Swiss cheese represent weaknesses. If all holes align there is no defence against a potential accident. The model forms part of Reason's model of system safety which is currently one of the benchmarks for socio-technological systems. The inclusion of latent causes has led to a reduction in operator blame. The method is inherently a Safety-I approach as the focus is on preventing accidents by eliminating malfunctions and faults (although the scope of these faults has expanded). An example of a maritime application of the Swiss Cheese model is Liu et al. (2013) who used a barrier-based approach to modelling offshore drilling blowouts.

AcciMap is an example of an accident model that adopts a system theoretical approach which uses multiple causal chains to model the events (acts and decisions) that are causally relevant to the accident. However, unlike traditional models, AcciMap superimposes these causal chains onto a predefined hierarchy based on the risk management framework developed by

Rasmussen (1997). The hierarchy differentiates causes based on the ‘remoteness’ of an event. The causal flow represents the propagation of events preceding the accident, events can propagate in any direction i.e. top-down, bottom-up and across events at the same level (Figure 3-2).

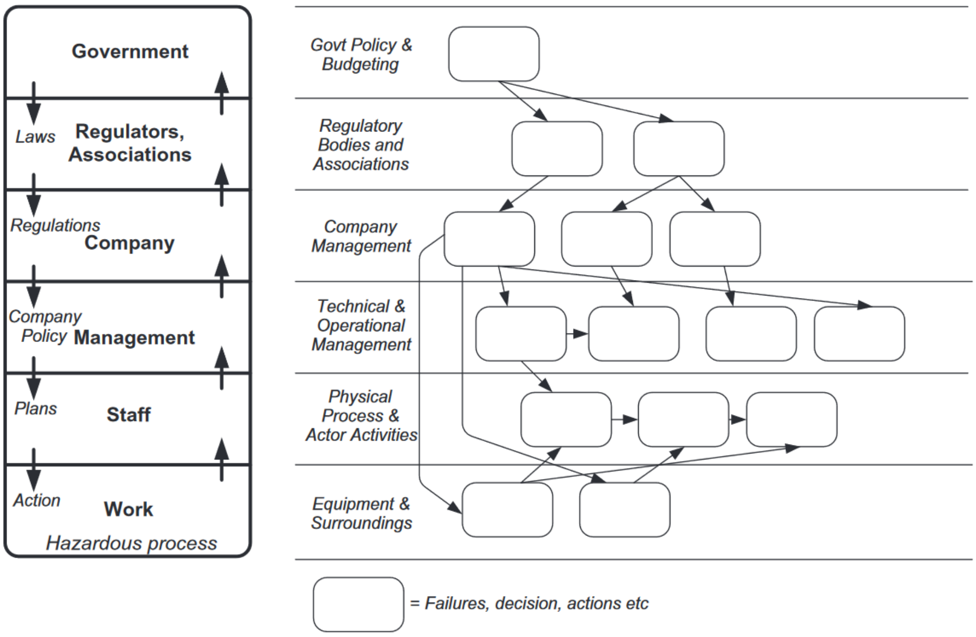

Figure 3-2 Rasmussen's risk management framework and AcciMap method (Salmon et al., 2012).

AcciMap adopts some of the principles of modern systematic safety analysis and ensures that a broad range of causal influences are considered. Despite considering a broader range of causal factors AcciMap adopts a deterministic causal approach and a preoccupation with finding what failed. These fundamental restrictions on the use of causality, borrowed from engineering and law, are common to every model of accident causation. AcciMap has been used to investigate many maritime accidents including the Sewol Ferry accident (Lee et al., 2017).

More complex non-linear systematic models have been developed based on a Safety-I approach including STAMP (Leverson, 2004) and FRAM (Hollnagel, 2012) (which also has the potential to be applied as a Safety-II approach).

Despite the foundation of system theoretical accident models of causation, they are seldom favoured over sequential models of accident causation and most experts and accident modellers still subscribe to simple models of linear cause and effect (Hovden et al., 2010).

There are also inconsistencies in the few practical applications of accident models based on system theory and the practitioner generally requires a sound knowledge of the underlying principles to effectively use these methodologies (Sklet, 2002).

3.3.2. Risk Assessments

Contrasting the restorative purpose of an accident investigation, risk assessments aim to proactively achieve safety outcomes by eliminating the potential for things to go wrong. The traditional approach to conducting a risk assessment is similar to the approach taken in accident investigations.

As with accident investigations, risk assessment methodologies replicate the engineering approach to improving the reliability of technological systems by identifying a potential for things to go wrong and then eliminating this potential. Despite being distinct from reliability, reliability models are commonly repurposed for safety analysis. In general, one of two approaches are adopted when conducting a formal risk assessment.

The first is a top-down approach which starts by identifying the potentially unfavorable system outcomes and then decomposes the system to identify the causes. This approach mirrors the traditional approach to an accident investigation except that the context is hypothetical. Fault trees (Vesely et al., 1981) are examples of this type of reasoning (Figure 3-3). For example, Celik et al. (2010) developed a risk-based modelling approach for maritime safety applications using fuzzy extended fault tree analysis. The analysis stated with top level failures and then attempted sub-divided systems into failures of both organisational and technological components.

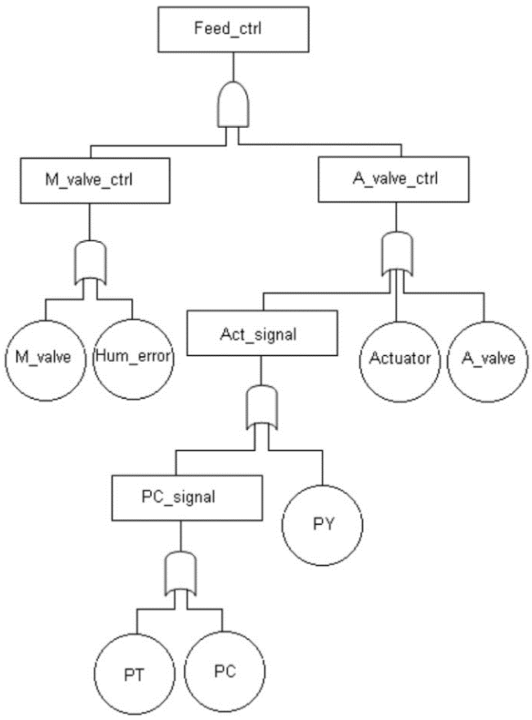

Figure 3-3 An example of a fault tree for the malfunction of a feed system (Khakzad et al., 2011).

A bottom-up risk assessment approach starts by decomposing the system and identifying potential fault modes, or hazards. The consequences of these failure modes are evaluated by assessing their sequential propagation through the system. The common risk methodology, failure modes and effects analysis (FMEA) uses this type of reasoning. Zahman et al. (2013) used FMEA analysis to simulate the risk of maritime collision in the Malacca Straits using AIS data.

Because risk assessments deal with hypothetical events rather than actual events, probabilities are often incorporated into risk assessments to quantify the likelihood and consequence of failure. These probabilities are usually derived from empirical failure rates (see the frequentist approach to probability in Section 2.8). The relationships between faults are usually deterministic (eg Naroozi et al., 2014, Abbassi et al., 2015).

The development of the qualitative aspects of causal models in risk assessments and accident investigations is critical for generating useful outcomes. However, the causal relationships in risk assessments are generally developed based on the intuitions of the risk assessor and the superposition of causal frameworks from other fields, especially law and engineering. A reluctance to acknowledge the importance of causality in safety analysis has led to discrepancies between the methodologies used in practice and their usefulness when applied to complex socio-technical systems.

The application of Bayesian or causal networks as a tool for reliability and risk assessment has increased dramatically over the past decade (Weber et al., 2012) and is commonly applied as a replacement for traditional tools such as fault trees and bow-tie analysis (Bobbio et al., 2001).

Replacing Safety-I risk assessment methodologies has been the extent of the adoption of causal networks in safety analysis. These restrictions do not match the original intended application of the method as a tool for storing knowledge and reasoning in an uncertain domain. Despite their restricted application, the flexibility of causal networks has been very useful in solving some of the limitations of methods designed to capture the Safety-I causal framework. These solutions include the ability to model common causes and the ability to accommodate inconsistent or incomplete information (Bobbio et al., 2001). Both these solutions have allowed traditional sequential models to capture more sophisticated ideas of accident causation.

Applications of causal networks to model system safety and analyse risk mostly use expert judgement to learn the structure of the directed acyclic graph (Celeux et al., 2006). The structural learning of a risk analysis model is usually conducted by an experienced system engineer and is often tailored to make the most of the data available.

For reliability applications a combination of approaches is often used to learn the parameters of a causal network. The data used to populate the conditional probability tables is rarely Bayesian in its nature and is often input directly from accident data, failure frequencies and frequentist human error probabilities e.g. Naroozi et al. (2013).

3.4. Weaknesses in the Current use of Causality in Safety Science

The primary assumptions of the Safety-I causal framework are that:

1. Systems can be decomposed into their physical components
2. Systems either behave correctly or they fail
3. When a system fails it can be traced to the malfunction of a component
4. Identifying and eliminating these failures and malfunctions will reduce systematic malfunctions

The approach and the assumptions underpinning Safety-I has several limitations that limit its ability to fulfil its purpose of reducing harm when applied to complex socio-technical systems. In part this is because the systems themselves have changed, affecting the value of information and the appropriate scheme for decomposition (Section 3.4.1). It is also because the goals of safety analysis have experienced conflict and have only relatively recently become well defined and independent (Section 3.4.3). The residue of disparate purposes still impacts the application of causality in safety. These shortcomings are most noticeable in the treatment of the role of humans within Safety-I models (Section 3.4.5).

3.4.1. System Complexity and Utility of Information

Socio-technical systems have changed dramatically over the past 50 years. These systems have become increasingly complicated and interwoven and are often being repurposed and generalised. The changes in systems and their applications has reduced the effectiveness of analyses based on the Safety-I approach.

The dramatically increasing number of components in modern systems propagates epistemic uncertainty. There are two reasons for this. Firstly, simply incorporating more components multiplies the existing uncertainty within the system. Secondly, as the number of components increases so does the interaction between these components. A Safety-I approach tells you nothing about the interactions and incorrectly assumes independence amongst components. A common analytical method for complicated systems is to utilise a coarser resolution. Systems, that were themselves the subject of analysis, become the building blocks of the more complicated systems. This approach does not address the increased epistemic uncertainty and instead cloaks it. Complete independence between components rarely exists and for socio-technical systems (that incorporate humans as decision makers) changes to the system inevitably affect other areas in ways that cannot be fully understood.

Systems are also being increasingly repurposed and generalised. When this occurs, the system is subject to a completely different set of boundary variables. The interactions of these exogenous variables with components within the system increase epistemic uncertainty.

The increase in epistemic uncertainty, caused by systems becoming more complicated and being repurposed, is insufficiently treated by the Safety-I approach. For complex socio-technical systems it is not enough to prevent or eliminate things going wrong to ensure things go right.

The preoccupation with failure when analysing complex systems is of limited value. This bimodal approach to functionality does not accommodate the complexity of components or their interactions. The lines between right and wrong blur and are less predictable and it becomes increasingly futile to describe system components and outcomes bimodally. This means the portion of possible failures incorporated by analysis decreases as does the ability to understand the effect of remedial measures when applying the Safety-I approach. There is also no guarantee that an iterative approach will morph the system into one that meets the assumptions of a Safety-I approach without losing functionality.

The Safety-I approach is a source of overconfidence that can be detrimental to the safety of systems. Focussing entirely on what can go wrong generates two biases. Firstly, a bias of overconfidence, as no effort is made to appreciate the state of incomplete knowledge. Secondly, the approach is a source of the what-you-look-for-is-what-you-find bias (Hollnagel, 2008) where safety analysis outcomes are influenced by preconceived ideas of failure modes. This is a specialised form of a confirmation bias (Nickerson, 1998).

3.4.2. Increased Public Expectations

Safety-I is a reactive concept because the malfunctions and faults are identified either by accident investigations or by risk identification. The process of identifying malfunctions and faults through iteration is comparable to the frequentists approach to probability and requires a large dataset. Increased public expectations of safety make a dependence on datasets derived from real world accidents increasingly unfeasible.

Higher expectations of safety also mean that high standards of safety are being applied to more fields. Unlike fields such as the nuclear industry or the aviation industry, these new fields lack the resources essential for the testing required to identify and rectify faults to an acceptable level. It also means the system cannot be iteratively designed to meet the assumption of the safety model.

3.4.3. A Refined Purpose

As stated above, the importance of safety has increased dramatically. The acceptable standards for safety have increased and these standards are being applied more broadly than ever before. This has made safety a topic worthy of analysis independently and without conflicting goals. The increased expectations of safety also exacerbate the impact of the shortcomings covered in Section 3.4.1.

Historically, efforts to improve safety have been conducted in conjunction with other purposes. Even today, safety analyses often strive to fulfil legal, scientific and engineering purposes in addition to reducing harm. Causal models that attempt to fulfil divergent roles often result in compromised outcomes as they utilise incompatible and sometimes contradictory information

Until recently, the judicial and safety purposes of an investigation could be carried out concurrently as the causes identified were, in general, mutually exclusive. This meant any cause could generally be neatly divided between those that were useful for improving the system (i.e. the technological failures) and those that were useful for the determination of blame (i.e. the improper actions of humans). Thus, improving the reliability of technological systems could be achieved concurrently with the determination of blameworthiness and liability because two separate causal models could be developed simultaneously without overlap.

However, in the 1970s and 1980s a series of high-profile industrial accidents occurred in systems where no obvious technological component had failed and no clear act of negligence had occurred (e.g. the Three Mile Island accident). This generated increased interest into the role and importance of humans within systems. Humans were included, for the first time, as a component in the analysis of system reliability. This meant the actions of humans were being examined to improve system safety, increase reliability and determine blame. The multiple purposes of safety investigations had become interdependent. One of many issues stemming from this interdependence was that the fear of legal repercussions was now at odds with the need to generate information about ‘human reliability’.

In a defence of dual purpose accident investigations in the maritime industry, John Kavanagh, a maritime lawyer, postulated that safety assessors are not adequately equipped with sufficient knowledge of causality to ensure valid and consistent outcomes and that subsequently, the safety outcomes of accident investigations benefit from a standardised approach to causality (Kavanagh, 2008).

However, like a projection on a map (see Section 2.4) the use of causality is necessarily targeted towards its purpose. The type of causality used in law is very specific and is appropriate for the purpose of determining blame. The universal application of legal (or any other field’s) causal framework is not conducive to better safety outcomes because their purposes are distinct. Although safety is now detached from other purposes, the causal frameworks governing the Safety-I methodologies remain detrimental to this purpose.

3.4.4. Measurability

Safety-I is defined as an absence of accidents or incidents which is measurable only by something not occurring. This inverted definition makes Safety-I as a quality, difficult to measure or improve. This is particularly evident in the case where no accidents or incidents occur or there haven’t been any for some time. The conclusion is that the system is perfectly or infinitely safe. The mantras of zero harm or zero accidents typify this approach. This assumes all accidents are preventable and that a system which has not experienced accidents cannot be made safer.

3.4.5. The Human Element

Most systems incorporate humans to some degree. These socio-technical systems rely on the interaction between humans and technology to achieve a desired outcome. The modelling of humans within Safety-I methodologies is a particularly compelling example of the shortcomings of the Safety-I approach. Under this approach, humans are treated the same as any technical component and the actions of humans are modelled bimodally i.e. correct-incorrect.

In simpler systems the find-cause, fix-cause approach is able to effectively reshape the system into one that is able to operate autonomously. Where epistemic complexity makes this impossible, the most commonly employed solution is to implement a human as a decision maker. Humans are good decision makers under uncertainty and are frequently employed to make decisions in complex systems.

The role of the shipmaster is an example of a human incorporated into a system for this purpose. A shipmaster's duties include ensuring the ship is properly crewed and equipped, well managed and navigated and compliant as per the standards of authorities and customers. A shipmaster usually owes duties to numerous parties and may come under the laws of more than one state (Cartner et al., 2009). The shipmaster must make decisions at the interface of various components and subsystems usually analysed independently and often with conflicting goals.

Modelling the actions of the shipmaster as an independent, bimodal component grossly simplifies this situation. When humans are incorporated into systems as decision makers under uncertainty, they have not been 'designed' or 'iterated' to conform to the assumptions of independent componentisation. Instead, they have been specifically introduced to cope with uncertainty. When humans are incorporated into systems for this purpose, their functionality cannot be accurately reduced to correct or incorrect behaviour for all contexts. The irony is that humans are necessarily incorporated into systems to make decisions where a model cannot and are subsequently judged on appropriateness of their actions by that same model.

Human error is cited as causative in a substantial percentage of maritime accidents (Hetherington et al., 2006). Identifying human error as the sole cause of an accident restricts the usefulness of recommendations for improved safety outcomes. Under the traditional find-cause fix-cause approach, components with a high failure rate need to be improved or replaced. This approach naturally leads to recommendations designed to improve or replace the human.

Recommendations designed to improve the human, such as better training etc. further the misconception that the decisions made by humans to smooth uncertainty can be constrained to an ideal. Moreover, when human actions are judged against an ideal that doesn't exist it promotes a blame culture that is detrimental to safety outcomes.

Further, recommendations that aim to replace the human without a complete understanding of their decision making process under uncertainty often lead to poor outcomes because the reason the human is implemented in the first place is because a deterministic algorithm is not applicable. In practice, for the system to continue to operate, the human is simply moved.

Resilience Engineering and Safety-II advocate stepping away from the use of causality in safety science and embracing theories of complexity and emergent outcomes (Hollnagel, 2012).

3.5. The Safety-II Approach

Safety-II is a new approach for conducting formal analysis to fulfil safety purposes (Hollnagel et al., 2006, Hollnagel, 2014). The purpose for conducting safety analysis remains unchanged from the Safety-I i.e. safety analysis is still being conducted for the purpose of reducing harm to people and property.

Safety-II redefines focus and objective of a safety analysis. Instead of focusing on identifying what may go wrong, A Safety-II analysis focusses on developing an understanding of how a system normally functions, or in other words, how things normally go right. Safety-II is different from reliability which is the percentage of things going right. In fact, Safety-II casts no dispersions about what is right and what is wrong. Rather the Safety-II approach is about understanding system functionality.

If a system were completely isolated from the outside world it would be possible to design it in such a way the it could function identically and expect the constant performance. In reality however, systems must adapt to variability that exists both external and internal to system functions. This is how system are able to manage variability an is the reason things usually go right. The primary objective of Safety-II analysis is therefore to understand and optimise system performance under inherit variability and uncertainty. Safety-II is closely linked to resilience engineering which is the process of improve a system’s potential to adapt to variability (see Section 5.2).

Safety-II does not limit itself to the analysis of what goes wrong. However, Safety-II does not mean ignoring instances of things going wrong, it simply advocates that developing an understanding of how a system functions is a more useful and natural approach which, in the long term, will lead to better safety outcomes.

The ideas underpinning Safety-II are not themselves new, however the formulation of these ideas and their application to system safety is compelling and convincingly addresses the limitations of the Safety-I approach and suggests a way past them.

Table 3-3 A summary of the causal framework underpinning Safety-II

	Predictive and Restorative
Purpose	Reduce harm to people and property
Objective	To develop an understanding and optimise how system functionality particularly the 'work-as-done' and a system's potential to manage variability.
Components	Functional Components e.g. *tend* the mooring line, *secure* the vessel Can also incorporate exogenous variables e.g. seastate.
States	Distributive states based on a broad range of variables.
Relationships	Descriptive Causal and probabilistic (Bayesian approach)
Salient	The descriptions of the system's functions and the work-as-done.
Measurable	Assessment of a system's ability to adapt to variability, more specifically: • *The ability to anticipate* • *The ability to monitor* • *The ability to respond* • *The ability to learn*
Outcomes	Recommendations aiming to increase the system's potential to cope with variability.

The Safety-II approach suggests that there is nothing intrinsically different between a favourable outcome and an unfavourable outcome. Safety-II considers system functionality identical for all outcomes which are simply a consequence of performance variability (Figure 3-4). In order to truly understand the occurrence of unfavourable outcomes it is a necessary prerequisite to first understand how all system outcomes occur and how the system actually operates.

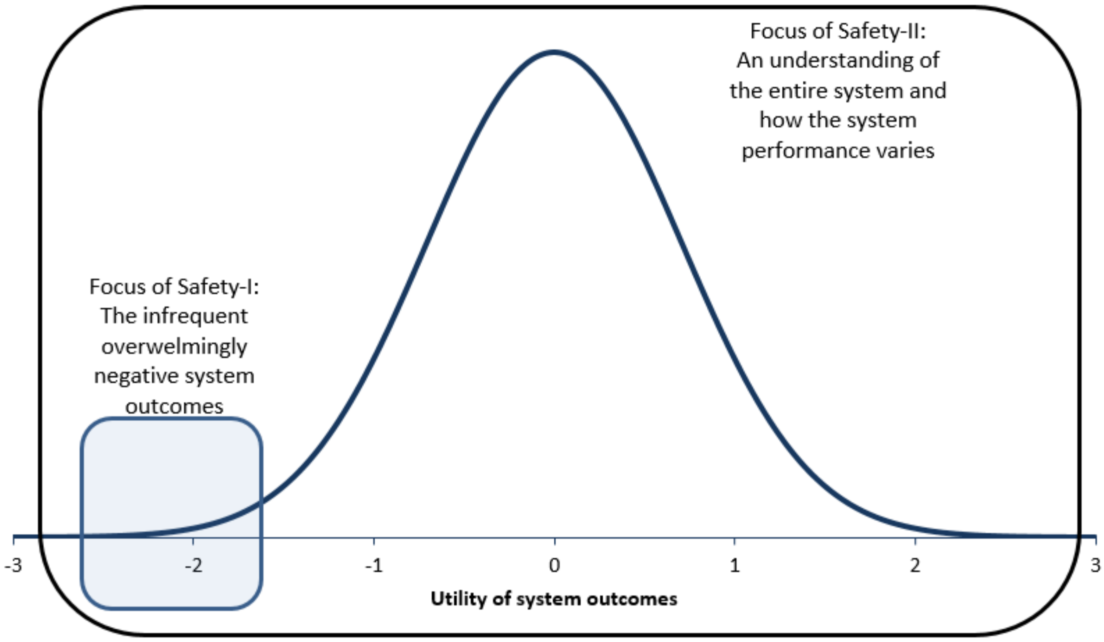

Figure 3-4 Different focus of Safety-I vs Safety-II

The difference in the Safety-II approach can be explained through the limitations of the Safety-I approach:

- Safety-II does not rely on preconceived failure modes to develop recommendations. Instead, Safety-II is a proactive model of safety because modelling the variability in system outcomes allows the modeller to anticipate when and under what conditions this variability becomes uncontrollable and make decisions to achieve greater system resilience without having to first identify an unacceptable risk or root cause.
- Safety-II does not use an inverse relationship as the basis for a definition of safety. Safety is, instead, defined as maximizing the positive outcomes. Because of this, Safety-II is examinable for all systems including those with an absence of accidents or incidence. This definition has the added benefit of merging ideas which require separate treatment under a Safety-I approach. This is especially noticeable with performance. Under a Safety-I approach performance and safety are mutually exclusive, inverted ideas which have to be balanced against each other however with the Safety-II approach the two concepts are directly linked by a utility of system performance.
- Safety-II does not rely on the identification of a root cause. Instead undesirable outcomes are said to be caused by variability within and outside the system. This is a more applicable idea which naturally incorporates epistemological uncertainty and means the system does not have to be perfectly decomposable in order to be modelled.
- Safety-II does not focus on the elimination of causes instead it aims to build and utilise an understanding of how system components interact in order to make the system better equipped to deal with performance variation. By focussing on developing an understanding of the system a knowledge base of how a system’s functional components interact and affect one another is developed. This reduces the problem of understanding the repercussions of intervention.
- Safety-II does not consider component functionality as bimodal. By acknowledging that good and bad outcomes are simply caused by variation in system performance we eliminate the bimodal, good/bad, outlook promoted by the Safety-I approach. Instead system components and the system itself can each take many or infinite modes. This is especially useful when modelling socio-technical systems. In Safety-II, instead of being viewed as a hazard, humans are viewed as a resource which is capable of providing resilience and flexibility. Work-as-done is an important concept in Safety-II and developing an understanding of the nature of human interactions within the system is a

key aspect. Humans are often incorporated into systems in order to provide resilience against system variation which cannot easily be modelled by regulators or designers without firsthand experience. It is rarely possible and potentially dangerous to constrain human behaviour to an ideal and is an argument against the bimodal notion of human error.

Despite its benefits Safety-II has received relatively little practical application compared to Safety-I methodologies. The first reason for this is that the concept is relatively new having been first formalised in 2014. As a result, the nomenclature of the technique is still in its infancy. A history of accident modelling using the Safety-I approach has also shown that the practical application of safety methodologies has trailed the latest theory, often by decades. Such a dramatic change to how a fundamental concept is treated necessitates a dramatic shift in mindset away from the fault-finding culture promoted over the last century. Key decision makers regarding safety such as regulators and managers are often removed from the actual system operation. This means there is a perception that the implementation of a work-as-done model is more difficult. This reluctance will likely wane as safety demands continue to increase in importance and increased system complexity proves the Safety-I approach to be inept.

3.5.1. Safety-II and Abandoning Causality

The standard approach to developing a safety model by decomposing a system into physical components and then relating these components using deterministic and causal relationships has received criticism from some researchers. Spearheading these concerns has been the observation that the outcomes of complex socio-technical systems cannot be deterministically predicted from the state of system components and the current practice of modelling humans as components in socio-technical systems misrepresents their role and restricts useful outcomes. These observations have led many leading practitioners to question the appropriateness of incorporating causal relationships into safety analyses (Hollnagel, 2014, Dekker, 2015)..

The main arguments against inferring causal relationships in safety analysis are derived primarily from the work of Erik Hollnagel, David Woods and Sidney Dekker (Hollnagel et al., 2006, Dekker, 2015, Hollnagel, 2014). The criticism of causality closely mirrors the criticism of the Safety-I approach. The main arguments against inferring causal relationships in safety analysis are detailed below.

The physical components that are typically modelled in safety analysis are restricted to taking bimodal states based on the component's functionality (e.g. safe-fail, function-malfunction). Relationships between components are then modelled with deterministic causal dependencies (e.g. if x and y are safe then z is also safe). Three assumptions must be true if this is a valid approach to modelling systems, these are:

1. The states of all components must be mutually exclusive and account for all possible outcomes.
2. The definition of any component's state must be known for the joint distribution of all endogenous and exogenous variables. There cannot exist a world where the definition of component states is ill-defined.
3. Knowledge of the state of every component modelled must allow determination of the entire system's state. This is a by-product of the deterministic causal relationships invoked between components.

The more accurately a system meets these assumptions the more appropriate and useful the scheme of bimodal states and deterministic causality is. The biggest objection to causality as it is currently used is that the causal scheme is being applied to systems that severely break these assumptions leading to inaccuracies, misinterpretations and decreased outcome utility.

Deterministic and linear causality have been repurposed from engineering design and law. This 'causal credo' has led to an overconfidence where complicated systems are being designed with an exponentially increasing number of components and component interactions. In these systems, imperturbable indeterminism in single component states and interactions propagate, couple and often resonate through the system leading to apparently emergent outcomes that cannot be deterministically predicted based solely on the state of components, a violation of Assumption 3.

Practically, the exponential growth of complicated systems has also led to the adoption of new schemes of decomposition at coarser resolutions. Adopting a coarser resolution often leads to violations of assumptions because the componentisation that warranted the use of deterministic causal relationships occurs at a finer scale than what is used for analysis. This can lead to pseudo-emergent outcomes unpredictable through analysis of the systems components (see Section 2.5).

3.6. A Defence of Causality in Safety Science

The criticism of the application of causality in safety analysis applies to the assumptions of the Safety-I causal framework and are not criticisms of causality itself.

The objections to the use of causality in safety analysis pertain its deterministic use as well as the focus on what has gone wrong or can go wrong. In many ways this reflects the common usage of 'cause'. Judea Pearl called this restricted notion of causality 'the actual cause'(Pearl, 2009), that is the event responsible for a given outcome.

The broader definition of causality (see Section 2.6) does not imply deterministic causal relationships between the states of variables. Nor does causality imply a 'reason' for accidents and negative outcomes or that a fault or cause can be found. The rationale for redefining causality as a notion broader than the 'actual cause', or the specific causal assumptions of the Safety-I approach, is that causal calculus offers a compelling tool for system analysis that is based on this broad definition.

Causality is extremely flexible and can be used to fulfil a variety of different purposes based on the relationships and variables considered salient. The primary problem with the use of causality in the Safety-I approach is that the assumed salience of information has been borrowed from other fields with goals that have diverged from the purpose of improving safety. This has limited the ability to generate useful outcomes. Rather than the abandonment of causality, reassessment of what constitutes salient information is necessary to improve the outcomes of safety analysis.

Causality has unique properties that are ideally suited to fulfilling the primary purpose of a safety analysis, which is to reduce harm to people and property and causality can be applied using both a Safety-I and Safety-II approach. Integral to both predictive and restorative safety analyses is the ability to, as accurately as possible, assess the effect of hypothetical interventions. Causality is the most natural concept that allows the prediction of effects under intervention, a statement that may even be tautological. Certainly, the symmetrical language of correlation does not allow for this type of query.

The primary reason for persisting with causality in safety assessments is that it is exceptionally useful in answering queries that remain central to fulfilling the purpose of a safety analysis. In particular, causal reasoning can answer three types of queries.

1. *Predictions. Would Y be y if we find X is x.*

   This is not a causal query but a correlatory query. It is possible to develop a probability distribution for a cause variable based on an observation of an effect variable. Such reasoning is useful when processing information during accident investigations and to make predictions in partially instantiated models such as risk assessments.
2. *Interventions. Would Y be y if we make sure X is x.*

   The ability to assess system behaviour under interventions is the most compelling argument for inferring causal relationships in safety analyses. A goal of all safety analysis is to develop recommendations that improve safety. Causality acts as an oracle to assess the effect of these recommendations, by including them as intervention of the current system.
3. *Counterfactuals. Would Y be y if X had been x.*

   This type of query is also unique to causal inference. More than being a test for liability, counterfactual statements can be applied to any causal model including probabilistic models. Counterfactuals align closely with human reasoning and allow the exploration of alternative realities. For this reason, counterfactuals are useful when developing recommendations following accident investigations.

Resilience Engineering and Safety-II advocate the replacement of causality with something else such as methodologies derived from the theory of emergence. As discussed in Section 2.5, emergence has limited descriptive power and virtually no explanatory power. Methodologies based on emergence also lack the intuitiveness of causal notion.

It is not in the spirit of Resilience Engineering and Safety-II to abandon intuitive methods in favour of abstract concepts. Instead the theories advocate a new qualitative causal scheme built with new components, a new purpose and upon new assumptions. The functional resonance analysis method (FRAM) is a good example of this new qualitative causal approach despite claims not to invoke any form of decomposition or causality. Figure 3-5 shows the typical graphical representation of the FRAM, as applied to a tightly coupled maritime operation.

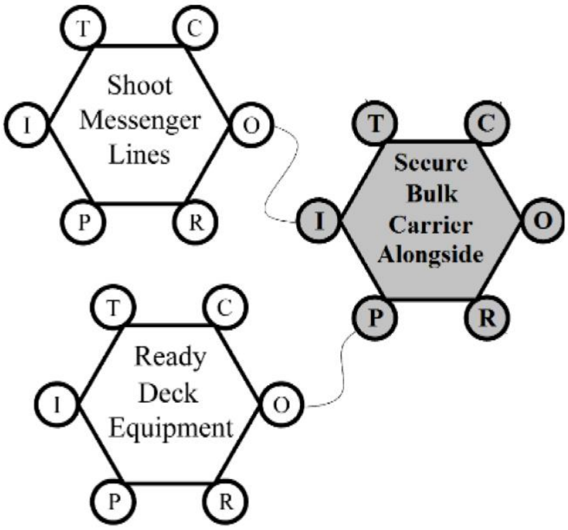

Figure 3-5 A partial, instantiated model of a novel maritime mooring operation

The FRAM incorporates a means of decomposition. The system is decomposed into functions rather than physical components. This method of decomposition is a different method to the physical components traditionally used but still divides the system for the purpose of easier analysis and more targeted recommendations. Additionally, a form of causality is also implied. The lines in the instantiated model run from the output of a function to aspects of other functions. A property of the output is causally relevant to an aspect of another function. This is an asymmetric and causal relationship; it allows the effect of interventions to be predicted. The FRAM is a qualitative method that relies heavily on interviews with operators to understand the work-as-done. In fact, the FRAM aims to elicit information about how humans adjust their work to meet variable and uncertain conditions, an aim that has causal implications. The FRAM uses a different method of decomposition and causality because it has reconsidered the salient information useful for the analysis of system safety and seeks to use the new perspective to generate more valuable outcomes.

Resilience Engineering suggests four qualities important to resilient systems, these are the ability to learn, anticipate, respond and predict. The ability to learn is aligned with the Bayesian approach to probability and human learning is closely aligned with the ability to create causal relationships through counterfactuals (Balke and Pearl, 1994). The unique ability of causality that allows anticipation under intervention is analogous to knowing what to do and hence, the ability to respond. Predict through correlation is analogous to the ability to anticipate and the ability to monitor relates to the ability to know what is salient. In short, the four resilient potentials are encompassed in the structure of a causal model, the method of decomposition and relationship between variables. The relationship between the abilities of a system with the potential for resilient performance and causal networks in detailed in Chapter 5.

It is therefore worth noting that a causal model is not only useful in assessing the safety of a system but that a causal model is also a primary determiner of resilience in a system and its ability to deal with uncertainty and variability.

Equally, the process of safety analysis is, itself, a socio-technical system, involving both humans and technology. Subsequently, any abstractions made to assist safety analysis should ideally be conducive to human cognition. Causality, being an innate component of human reasoning, aligns the process of safety analysis with human intuition.

Safety analysis is dependent on humans not only to process and order the information, but also as a source of that information. Utilising a causal calculus allows the causal information provided by participants to be encoded within the analysis without translation. Adopting causality in safety analyses is an example of human-centered design as the process is aligned with human intuition.

This approach is so innate that all safety methodologies adopt a form of decomposition and a form of causality, either implicitly or explicitly. The functional resonance analysis method is a safety methodology based upon the qualitative assumptions of Resilience Engineering rather than engineering or law.

3.7. Summary

The prevailing Safety-I approach to causality in safety analysis is based on deterministic causal relationships. These relationships attempt to map the propagation of faults and failures through the system. This approach closely mirrors that used to improve engineering design and the use of causation in law as a tool to assign blame.

The assumptions of this type of causality are not suitable for the safety analysis of complex systems, where outcomes cannot be deterministically predicted using the traditional form of componentisation. The treatment of humans as another component within a system is a particularly inaccurate discretisation and is detrimental to safety outcomes because it fosters a culture of blame.

Safety-II and Resilience Engineering proposes emergence based concepts as a substitute for causality. However, it is the assumptions underpinning the current use of causality in safety analysis that have led to the shortcomings. Causality itself is necessary and inescapable to derive useful outcomes from any system incorporating uncertainty. The challenge is to select a framework that allows such useful outcomes to be derived.

Chapter 4 develops a causal framework for safety analysis using the qualitative observations underpinning Safety-II and causal networks. This amalgamated approach is also applied to a novel maritime operation. Developing a methodology for establishing causal models based on the new qualitative framework bridges the gap between the latest theories of systematic safety and their practical analysis.

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and,

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Chapter 4 Using the Functional Resonance Analysis Method to Structure Causal Networks for Safety Analysis

4.1. Introduction

Following the exposition of causality presented in Chapter 3, this chapter focusses on the more pragmatic issue of developing and explicating a causal framework that recognises the importance of considering human factors in the safety analysis of socio-technical systems. Justification for the development of a new causal framework follows from the main conclusions of Chapter 3, namely:

1. The notion of causality is extremely useful in system analysis because it permits counterfactual and interventional queries that are not possible using other regimes and, because causality aligns closely with human cognitive processes; and,
2. The current causal framework, adopted in contemporary safety analysis, is not fit for purpose because of the increased complexity of modern socio-technical systems and an increased emphasis on safety outcomes that are removed from legal or financial motives.

The ideas outlined in Chapters 2 and 3 emphasise the relativity of causal relationships. Causality is only apparent in a world that is discretised and simplified such that it adopts a particular point of view. A universal causal framework does not exist and all frameworks are incomplete but some can be useful. The guidelines for causal representation developed in this chapter are especially targeted at understanding the role of humans in socio-technical systems and their interaction with the environment. This causal framework does not fulfil all analytical purposes nor does it claim to replace current methodologies. Instead, the presented methodology aims to provide greater insight into an area to which it has been traditionally difficult to apply notions of causality and quantification.

The methodology developed in this chapter superimposes the qualitative framework of the Functional Resonance Analysis Method (FRAM) onto causal networks, a probabilistic graphical model. Because the relationship between elements of the model evoke causality, the network is, more specifically, a causal network. A brief overview of the FRAM is given in Section 1.2. The FRAM is based more generally on the concepts of Resilience Engineering and Safety-II outlined in Chapter 2. A theoretical introduction to both Bayesian and causal networks is also given in Section 2.10.

Causal networks are being increasingly applied to problems in reliability engineering and safety analysis. For the most part these applications have been limited to extensions of pre-existing risk assessment models, such as fault trees and failure modes and effects analysis (Stamatis, 1995). The causal framework adopted in these applications has been copied from the pre-existing models. As such, these applications experience the same limitations common to Safety-I methodologies (Section 3.4). However, causal networks are not restricted to a specific causal framework and it is only the prevailing qualitative assumptions of Safety-I that have limited its application with safety science.

This chapter details two approaches for learning of the structure and parameters of causal networks. The first approach adopts a Safety-I causal framework and builds a model based on frequentist failure probabilities (Section 4.4); the second model (Section 4.5) uses the functional resonance analysis method as a template for a causal framework that is then parameterised using Bayesian probabilities (see Section 2.8). Both networks are applied to the floating harbour transhipper concept (FHT), by modelling its unique ship-to-ship transfer operation. An overview of the FHT concept and its ship-to-ship transfer operation is given in Section 4.3.

The Safety-I network is focussed on the simplified reliability of a ships propulsion and steering system during the ship-to-ship manoeuvring operation. The componentised aspects of a ship's propulsion system combined with an abundance of data, make it typical of systems where the usual approach works relatively well. The Safety-II methodology is applied to the ship-to-ship manoeuvring operation of the FHT, although it is broader in its scope and focusses on the human element of the operation.

The differences between the two methodologies as well as the advantages of the new approach are discussed in Section 4.6. Further analysis, including the development of recommendations and interventions to improve system safety, is covered in Chapter 5.

Chapter 5 Functional Causal Networks and Resilience

5.1. Introduction

This chapter explores the ways that the functional causal networks developed in Chapter 4 enhance a system's potential to adapt to variability. Section 5.2 introduces the concept of resilience and Resilience Engineering. Resilience is the quality that allows systems to adapt to variability. A system potential for resilient performance is influenced not only by actions it may take but also the state of knowledge, this relationship is explored in Section 5.3. There are four abilities that are sufficient and necessary to enable resilient performance, Section 5.4 shows how functional causal networks interact and enhance each of these four abilities. Section 5.5 uses the Safety-II causal network developed in Section 4.5 to make recommendations for the floating harbour transhipper's ship-to-ship manoeuvring operation. These recommendations are developed by generating knowledge of the system's functions using causal networks and interviews.

5.2. Resilience Engineering

Chapter 6 Summary, Conclusions and Future Work

6.1. Summary

The aim of this study was to justify and develop a resilience-based causal framework and methodology for the safety analysis of a novel maritime transhipping operation. Causality is a vital tool for developing safety recommendations although the prevailing causal framework is inept for the safety analysis of complex socio-technical systems. This study used a resilience-based approach to learn the structure of a causal network that, in turn, was used to develop safety recommendations for a novel and untested maritime transhipping operation.

An introduction to the thesis was provided in Chapter 1. The subject of causality was introduced in Chapter 2, emphasising the importance of causality as a tool for human reasoning and providing a theoretical precursor for causality as it is used in this study. Chapter 3 explicated the assumptions and shortcomings of the prevailing causal framework adopted in safety analysis and justified the need for a new causal framework when analysing complex socio-technical systems. The Safety-II approach to safety analysis was introduced also in Chapter 3 as were the corresponding arguments against the use Safety-I use of causality. Chapter 4 proposed a new causal framework based on the Safety-II approach. The Chapter also developed a new safety methodology utilising the functional resonance analysis method to learn the structure of causal networks. The new methodology was applied to a novel transhipping operation, the Floating Harbour Transhipper. The new methodology was contrasted against a traditional Safety-I analysis using causal networks. Chapter 5 explored how the new methodology, developed in Chapter 4, can be used to analyse and improve the safety of a complex socio-technical system. The relationship between resilience and causality was developed and the passive safety benefits of developing a functional causal network. The use of causal networks to direct enquiry and develop safety recommendation was also discussed.

This chapter provides a thesis summary (Section 6.1) as well as presenting the key theoretical (Section 6.2.1) and methodological findings (Section 6.2.2) of this study. The study's limitations are discussed in Section 6.2.3 as are suggestions for work that could extend these findings in the future (Section 6.3). Finally, a brief account of this study's potential implications in safety analysis is given in Section 6.4.

6.2. Findings and Limitations

6.2.1. Theoretical Findings

- Causality plays a central and necessary role in safety analysis. As a pillar of human reasoning causality is vitally important to safety analysis, just as it is to any other field of human inquiry. Causality provides a predictive power and even more importantly allows an understanding of the effect of hypothetical interventions. Recently, some safety researchers have advocated against the continued use of causality. This study demonstrates that these criticisms are focussed on the particular causal framework currently used in safety analysis and that there are very good reasons for adopting a causal approach to safety analysis, albeit using a different framework.
- The concepts of Safety-II and Resilience Engineering can be incorporated into a causal framework. The prevailing causal framework used in safety analysis borrows extensively from law and engineering. This framework is unfit to achieve the desired safety outcomes in complex socio-technical systems. In this study the ideas contained in Safety-II and Resilience Engineering have been used to develop a new causal framework. The new causal framework maintains the conceptual ideals of Safety-II and Resilience Engineering, while also providing the advantages associated with developing causal relationships.
- Safety-II's concept of performance variability can be treated probabilistically. Safety-II is closely linked to Resilience Engineering. This is the notion that a system's safety can be assessed by developing an understanding of a system's potential to adapt to variability. Variability in this sense is not the aleatory uncertainty irreducible after long range trials. The arguments against quantification and the use of probability presented by Safety-II advocates are, in fact, arguments against this frequentist approach which treats probability as softened truth values rather than an expression of doubt. The concept of resilience is closely aligned with the Bayesian approach to uncertainty. The Bayesian approach conserves the language of probability and is compatible with the Safety-II approach. This is because it expresses beliefs rather than truth, incorporates a broad range of information, is updatable when new information becomes available and does not require long running experiments.

- There is a strong relationship between Resilience Engineering and causality. The four potentials of Resilience Engineering (to learn, to anticipate, to monitor and to respond) are the qualities sufficient and necessary for resilient performance, i.e. the qualities required to accommodate uncertainty and adapt to variability. Causal modelling is the reasoning tool that humans use to achieve the same purpose. Causality is the tool that facilitates the four potentials in how we reason about the world and, through the inclusion of human judgement in socio-technical systems, is also the reason many systems are able to perform resiliently.

6.2.2. Methodological Findings

- Causal networks are non-specific to any particular causal framework and unlike many Safety-I methodologies are able to implement a Safety-II approach to analysis. This study uses the functional resonance analysis method (FRAM) to develop the structure of a causal network. Compared to a Safety-I approach there is significantly less rigidity in the functional causal network. This is advantageous as it allows the network to closely represent the functionality of the system. In this sense the causal network acts more as a knowledge database that incorporates and structures information about how a system works. Using the FRAM to structure causal networks extends the current application of both safety methodologies.
- Causal networks are able to incorporate a broad range of information, especially expert testimony. The functional causal network, developed in this study, incorporates the causal and probabilistic essence of this information while also providing standardisation and abstraction that allows information to be transferred and utilised effectively. Additionally, the functional causal network directed further inquiry, explored context specific information and assessed the potential for resilient performance in order to develop safety recommendations. These safety recommendations benefitted the Floating Harbour Transhipper, a proposed and untested transhipping operation.

6.2.3. Limitations

- There is presently a lack of information available to fully utilise a Safety-II approach. This is hardly surprising as the new approach was only formalised in the last two decades. The lack of readily available information is also due to Safety-II's focus on the work-as-done, meaning a lot of information exists informally. The alignment of the causal frameworks between Safety-I and engineering mean that a lot of information is able to be repurposed. This is not the case when adopting a Safety-II approach. The information also does not exist in a condensed and readily digestible statistical format. While it is more cumbersome to cultivate information using a Safety-II approach, the additional effort extracts pertinent information regarding how a system functions that is essential for deriving meaningful safety outcomes in complex socio-technical systems.
- The functional causal networks developed in this study lacks the structure that would propagate its widespread application. Despite their benefits, Safety-II and Resilience Engineering have received relatively little practical application compared to Safety-I methodologies. One of the initial objectives of this study was to give the methodologies of Safety-II and Resilience Engineering more widespread appeal by providing them with the languages of causality and probability. In this sense the study was only partly successful. The causal networks enable a transferability of results and a level of abstraction that allows concise exploration of a broad range of contexts. However, there is still significant flexibility when learning the structure and parameters of the Safety-II causal networks as well as the methodology for developing safety recommendations.
- This study may create confusion regarding the role and definitions of probability and causality. The commonly accepted definition of causality connotes a degree of determinism and, in many cases, blame. When probability is used, in any field, it is more commonly meant in the frequentist sense, especially in engineering. In this study both probability and causality are used with significantly different definitions. This may cause some to draw parallels with Louis Carroll's Humpty Dumpty: '*When* I *use a word…it means just what I choose it to mean — neither more nor less.*' (1947).

  However, these definitions are well established, and in both cases, the redefined topics are justified generalisations of the commonly used terminology. The limitation is that using these terms, however intended, either promes the use of the currently accepted definition which in turn encourages the Safety-I approach, or creates friction with those who see the shortcomings of the current use of causality and probability.

6.3. Future Works

- This study could be extended by incorporating a stronger focus on modelling the decisions people make that allow a system to function correctly. Influence diagrams are an extension of typical causal networks that include decisions and values (Jensen et al., 1994). Extending the functional causal networks to include aspects of decision making is a further step towards understanding the work-as-done. More specifically, of what decisions must be made and the variables affecting these decisions. The utility of outcomes should also be explored and considered. Prospect Theory (Tversky and Kahneman, 1992) is one approach that aims to understand decision making and judgement under uncertainty. Using influence diagrams has the added benefit of being able to place a value on information. This value can be used to assess safety recommendations based on the reduction in performance variability. Placing a value on information further highlights that safety can be improved both actively, by increasing the system ability to adapt to the variability and passively, by obtaining more information.
- Increasing standardisation to the processes used to develop the functional causal network and the development and analysis of recommendations would benefit the take up of the approach by safety practitioners. As described above, standardisation has both positives and negatives. On the one hand, greater standardisation offers more transferability and appeals to a greater number of safety practitioners. However, standardisation limits a method’s ability to model intricacies of a particular system. For the methodology described in this study, and Safety-II approaches generally, the benefits of more standardisation outweigh the disadvantages.
- Developing structured interview techniques that elicit information salient to the Safety-II approach would reduce the variability in the quality of safety analyses. How to extract useful information stored in the mind of operators and experts is currently more an art than a science. There is no greater determiner of the outcomes of a safety assessment than the quality of the information that goes into it. A formalised approach to conducting interviews and extracting useful information would help reduce the variability in Safety-II risk assessments. This study contends that these interview techniques should seek to identify relevant variables, elicit causal relationships and determine their strength.

6.4. Implications

Safety analysis is divided into two groups of practitioners. The majority are everyday safety practitioners who adopt a Safety-I approach, these practitioners are less focussed with the conceptual underpinnings of the method and more concerned with practical applicability or quantitative aspects of the methodology. The other group are the new wave of safety practitioners who have highlighted the shortcomings of the existing approach and who have developed the various aspects of the Safety-II approach. The latter group disparage the current safety methodologies and have explored other avenues for conducting safety analysis. Both groups of practitioners are genuinely concerned with improving safety. This study has implications for both groups of safety researchers and for the field of safety analysis more broadly.

For Safety-I practitioners this study highlights the assumptions and shortcomings of the prevailing approach when applied to complex socio-technical systems, especially when considering the role of humans. This study draws attention to the impacts of qualitative assumptions on safety outcomes and shows that Safety-II and Resilience Engineering align with causal intuitions. These ideas can be directly implemented using existing and familiar concepts such as causality and probability. Further these ideas can be condensed and quantified into existing methodologies, such as causal networks.

For Safety-II practitioners, this study emphasises the importance of causality in safety analysis, a concept that many Safety-II practitioners have argued to eliminate. Causality is aligned with the concept of resilience and mirrors the way humans utilise information to make decisions under uncertainty. It also introduces the Bayesian approach to probability as a standardised language for accommodating uncertainty. Additionally, this study shows that causal networks, to date applied as a Safety-I methodology, are able to model complex socio-technical systems from a Safety-II perspective and succinctly incorporate detailed qualitative information regarding system functionality.

Causal networks structured using different causal frameworks, such as Resilience Engineering, have great potential in safety analysis. It is hoped that future methodological developments standardise the approach described in this study so that both causal networks and Safety-II are more widely utilised in practice. Additionally, it is hoped that theoretical developments in safety analysis recognise the importance of causal reasoning.

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Appendix A: Notes from Interviews with Marine Professionals

As discussed in Chapter 4, this Appendix provides a more complete record and the salient points from six interviews conducted with a range of marine professionals. The aim of the interviews was to acquire a better understanding of the work-as-done, which in turn assisted the development of the FRAM model for the FHT ship-to-ship transfer.

The participants included naval architects, marine pilots, marine engineers, master mariners and seafaring captains. Each participant had considerable experience with either ship-to-ship or transhipping operations.

Interview #1: Marine Pilot

Date: 24/11/2016

Background and Experience

- The participant has worked as a marine pilot at Port Hedland, Western Australia, for the last 7 years, predominantly on Cape size bulkers up to 268000t DWT. Port Headland is a tidal port in a cyclonic area.
- Prior to this, the participant worked as a marine pilot at Bell Bay, Tasmania, on Handy max and some Panama bulkers. Bell Bay is a narrow river port with tight bends and strong currents.
- The participant also worked as a marine pilot for one year at Mobil's Port Standback in South Australia which used a jetty and single point mooring (SPM) arrangement, this was presumably on tankers.
- The participant spent time at sea prior to this, working predominantly on tankers for BHP transport. He completed his MBA.

On the FHT Concept Overall

- It is very different to my prior experience, except for the SPM, however I have discussed similar operations with several colleagues who regularly engage in the transfer of bulk commodities.
- The biggest challenge facing the FHT is operating in an open seaway which is subject to changing wind and tide.
- Berthing the export vessel alongside the FHT as opposed to a wharf or jetty also presents two additional challenges:
- Firstly, the point of reference is a movable object whereas in port it is fixed, this makes it significantly more difficult to line things up.
- Secondly, the interaction between the two vessels can be significant, the Cape size vessel in ballast condition still displaces up to 140,000 tonnes, this means you are pushing a lot of water onto the FHT.
- Operating in seas between 4 and 4.5 metres may be feasible in head seas if you have tugs and a pilot. Roll is the main concern for an operation like this. Being able to effectively

control the FHT’s heading, through use of stern and bow thrusters, reduces a lot of the roll concerns.

On the Need for Tugs

- You will definitely need tugs for this type of operation, even in good conditions. This is in part due to the need to manoeuvre in an open seaway but more importantly for redundancy.
- In Port Hedland we actively steer the bulkers using the tugs because failures happen so frequently. Common issues include main engine and rudder failure as well as issues with crew competency.
- Things go wrong all the time with engines at Port Hedland - we typically have about 10 per month out of 500 movements. This can be something minor like an engine slowdown in a channel but are often things like sensor failures which shut down the engine. Maintenance and crew competencies are also issues. It is common to have issues caused by unclean filters or opening the wrong valve for instance.
- Bulkers are at the bottom end of the shipping world, low freight rates mean the ships are built and maintained on a very tight budget and rarely include anything more than the minimum required. The crew are paid low wages and often have insufficient training.

On the Need for a Pilot

- A pilot would also be essential for this type of operation. Ship Masters are not trained for this type of operation and given you are using the commercial shipping fleet you have no control over the crew’s competency, which varies considerably. Ship masters often have little experience with ship handling and the most they do is take a ship to anchor in a busy area. As an example, in Port Hedland Masters cannot keep away from the reefs without the help of Vessel Traffic Services (VTS).
- If you are using your own ships then you will be able to train and control the competencies of the crew and ensure they have undertaken specialist training, but if you are using the international fleet without a pilot you would end up with holes through the FHT. There is so much variability in the training the crew undertake they can have anything from AMC level to virtually nothing. The crews on our vessel are maybe 40%

Filipino, 30% Chinese, some Burmese, a lot of the vessels are Greek owned and have Greek of Turkish officers.

- All pilots have Master I certificate and are experienced with cargo handling operations and so they can stay on board and supervise the transfer of cargo. The pilot brings the ship in, ties it up and controls the cargo transfer. You would need rotational pilots for the 3-4 days required to finish the cargo. A similar operation occurs in Port Latta.

Information and Procedures before Boarding

- I operate in a high volume port with a fixed roster, this means a lot of the shore based planning work is completed by others.
- The crew of the vessel will be typically sent information on:
  - How to prepare the vessel
  - Mooring arrangements
  - Weather ranges and limits
  - Tidal and current predictions
  - Liaising with the production guys also ensures transfer timings are smooth.
- As a pilot I will:
  - Study the environmental conditions for the manoeuvre and the length of the transfer
  - Place a contingency plan for bad weather
  - Prepare the Master Pilot exchange form
  - Look at mooring arrangements
  - Look at tug arrangements
- The Pilot will be sent berth-to-berth plans from the bulker which typically consist of simple waypoints. They also have pilot information cards which provide basic ship information, particulars, a picture, speeds and engines settings. They don’t typically tell you that much and the speeds are not that relevant anyway in shallow water.
- For some operations you might need to have a meeting with the mooring crew and tug crew beforehand, if you have the time this is a great idea and saves a lot of hassles. This would be essential for the something like the FHT’s operation.

- It is also important to think about communication lines prior to operation. North-west Australia is an area of high skip so private means of communication should be considered. For an operation like the FHT communication is vital.
- A Safety Management System (SMS) is essential to manage and organise the many variables. There is still a vast amount of information which is not covered in the SMS and has to be stored in your head. Various stages of checklists typically form part of a good SMS. These checklists are essential for operation like this. Checklists are undertaken three days out, 1 day out etc. Both these and the Master-Pilot exchange is a trigger point both to remember information and also to collect the information you require before you go.
- There is considerable variation in how the vessels themselves conduct their checklists and apply their SMS. For most vessels, the SMS sits on a shelf and is never consulted. This is part of the reason Pilots are so important.

Undertaking a New Operation

- When undertaking a new operation, it is important to consult all personnel and get their input throughout the design stage. Pilots and experts should be consulted as should the Bureau of Meteorology for the environmental information. This allows a basic knowledge to be built up and procedures to be designed.
- Training is an important element when undertaking a new operation. It is important to employ a range of training medium. Simulations are great for training and getting an understanding of procedures, however there is often considerable difference between the simulation and real life. Experiencing similar operations is a great way to get experience with new operations. Most places will let you watch operations and it is a great way to learn, however there may be some issues with commercial sensitivity.
- When planning for the first operation it is important to start out small: this means undertaking the operation in calm seas utilising high tug power. Often it is a good idea to start with a smaller vessel like a Handymax or Panamax if it is compatible. For an operation like this, quirks will often appear that you haven't seen before. Starting small helps control the risk and stops things becoming unmanageable. The true operational limits can never really be known until you have experienced them so it is important to take baby steps.

Boarding the Vessel

- We usually head to the office an hour before going aboard, this gives time to finalise paperwork etc. Recently, Port Hedland has moved to an electronic scheduling system which is still in its development stage.
- Whether a pilot boat is used or a helicopter depends on economics. We use a helicopter for all Cape size movements. This is because our volume is so large the additional time required to transfer pilots by boat would require employing more pilots. We have three helicopters in operation at the moment, as well a pilot boats. The redundancy is essential as the helicopters are always down for maintenance. The pilot boat is also necessary for search and rescue (SAR) capabilities as well as redundancy, for example there may be a situation where you can't use a helicopter. There are additional risks associated with the transfer from the pilot boat to the bulker and the bulker has to create lee, but in general there is not a lot of difference. The helicopter allows a good representation of the wave conditions, location and deck fitting while the pilot boat gives you the opportunity to get a rough idea of the drafts, which can and do vary wildly.

Communication Aboard

- Masters are always on the bridge when you embark, once aboard you complete the Master-Pilot exchange. On good ships the forward and aft crew come to the bridge as well. You would certainly do that for an operation like the FHT. The pilot would come aboard a lot earlier than a normal operation so they could spend a good 10-15 minutes running through the operation and going through paperwork. The waters around the STS transfer location will determine how far out the pilot is needed. There is not a lot of information and assistance provide by the shipping company to the Master and they are generally quite willing to accept the Pilot's advice and assistance.
- For an operation like this, communication with the Master and deck officers is critical. Communication and language difficulties are a big issue when communicating with the Master. This is particularly true for Chinese Masters who learn only very basic English. They are fine for things which are standard and normal but trying to communicate things which are non-standard or out of the ordinary is challenging. When things are going wrong is when it is at its worst. It becomes very difficult to get the message across. We

resort to drawing diagrams frequently and it is often what is needed to get the message across.

- The competencies of deck officers vary considerably and communicating with them is also a challenge. Typically, you speak to the Master who then relays the information to the crew. This means you are quite removed from speaking to them. If the master gives instructions in English, you try to keep an ear out to make sure the right information is being relayed. If, however the Master gives instructions in another language you are out of the loop completely.
- Providing the crew and the Masters with a lot of pre-information is very helpful. It pays to send out information as soon as the ship is chartered. This information could include operational details, paperwork and checklists. A video or multimedia presentation is also one of the best ways to convey information.
- The engineers usually stay below, although there are frequently issues with machinery.

Manoeuvring

- The bridge on a ship has not changed much since I started, and probably 10 years before that. Better radars and Electronic Chart Display and Information Systems (ECDIS) are the two main changes.
- Automation is a good thing, provided it works well and people know how to use it. The varying levels of crew competency can make automation a hindrance. Bridge resource management and working together on the bridge is another great idea in theory but the realities of it are very different. Often you are on the bridge by yourself while the Captain has gone below. The ideal world and the reality are nowhere near each other.
- My own limits have been push primarily by environmental variability. The training of pilots is slow, comprehensive and thorough, such that uncertainty through unfamiliarity is not really an issue. The environmental variability can still surprise you though. In Port Hedland I have experienced large squalls, while in Bell Bay it was the tight corners and strong currents.
- Generally, I do not feel significant stress or time pressures unless there is an emergency. The primary reason to abort a manoeuvre in the case of the FHT would be weather conditions. The options for aborting depend on how much water you have to manoeuvre.

- The portable pilotage units are great and include an STS module. The Portable Piloting Unit (PPU) greatly reduces your work load, particularly in an emergency and also allows for the communication of critical information between the Bulker and the FHT.

On Mooring

- The deck fittings on board Cape size vessels can and do vary considerably both in terms of their ratings and locations. The way bitts and fairleads are rated seems to have changed over time and is not standardised. It is an area which needs improvement. At the moment, it is largely left to the dockyard. A direct pull on a bitt is different to a turn up, but is not usually considered in the ratings. We also commonly see fairleads which are rated lower than the bitts. Most bitts are rated between 70 and 80 tonnes but we still see some which are rated less than 50 tonnes. When under tow we can easily see loads over 150 tonnes meaning the safe working limits are often exceeded, in an emergency you do what you have to do. We have not ripped a bitt of the deck yet. We are seeing more and more ships with larger bitts aft, rated up to 150t.
- Typically, the spring line would go over first followed by a breast line. Opinion varies on whether you run long mooring lines, which you then keep tight while manoeuvring into position or wait until the ship is in position before throwing the lines. The difference in air draft between the two vessels may present some challenges. We use mooring boats to get the lines across, compressed air launches are another good option and are common in the tanker industry.
- Using the FHT lines is a very good idea. The lines on bulkers vary considerably and you have no real control over them. We have seen lines on Cape size ships which are rated highly but part at very low loads. We rarely use the lines themselves to manoeuvre, I generally use the main engine. There is no real reason why you can’t use the lines to manoeuvre. One option may be to pull the bulker up between 0.5-1.0 B from the FHT throw the lines and use the FHT winches to bring the two vessels alongside with the tugs in a safety position.
- The variability in the location of deck fittings could lead to some problems with compatibility alongside the FHT. At Port Headland, we are often left with very short breast lines. In a narrow part of the channel we had problems with interactions and with vessels ranging or being sucked off the wharf. We had many lines parting. We have since

adopted a system (mooring master) where vacuum pads hold the vessel in place. The system is great but very expensive. It has been designed with a lot of redundancies and we have not had a failure in four years of use. Additionally, where the vessel would move one metre using lines, she moves just one cm using the mooring master. The system is operated from the ship side so they can go as they please. The company is based in New Zealand and is quite innovative and may be worth contacting.

- The crew of the bulker can struggle when a mooring operation differs from what is normal. It is normal practice on similar operations to have a mooring master go aboard the bulker. I would also recommend an additional supervisor forward and aft to monitor the operation. Transferring personnel between vessels may be required if using mooring supervisors. This may be challenging as in head seas you won’t have a lee and won’t be able to transfer in larger seas. Using a helicopter isn’t always an option.
- Having a fixed fendering system on the FHT is the preferable option and would work well.

Interview #2: Ship Master

Date: 09/10/2016

Background and Experience

- Participant has worked as navigation officer and has occasionally engaged in ship-to-ship transfers. Was Second Officer on a 75,000t tanker conducting full time ship-to-ship transfers in West Africa and Master of an 80m bunker barge for 2 years completing 5-6 STS transfers daily.

Overall Thoughts on STS Operations and the FHT

- Experience is the key to the FHT operation. The first few times we conducted an STS transfer we experienced big difficulties and delays. But after that everyone became quite well versed with the operation and the procedure ran quite smoothly and not much time was required to prepare.
- We had the checklists from OCIMF however we rarely used them and usually just ticked the box. We normally did things fairly similarly with the large vessel. However, large vessels behave unpredictably and we needed to be flexible and adaptable with our work. We would adjust the way we did things (e.g. approach, moored, mooring arrangement, mooring sequence etc.) to cope with all combinations of conditions. The way we did things was governed by our experience and the experiences of the vessels around us and not by the rules outlined in procedures. Our adjustments were relatively small for the large vessel but were much larger when we were undertaking bunkering operations. The operating limits were never governed by procedures but rather experience.
- With the FHT there is a great opportunity to design STS transfers properly. A lot of things could have been made easier. Better design of winches and bollards. Better mooring lines which are easy to handle. Good workable fenders and line throwers were some of the things which would have been the most beneficial to us.

Receive Email from Office

- An email is received from the office informing the crew of the date, time, cargo type and amount to be transferred. The email is typically received the day before the operation.
- The email is often received much later than when it was sent as there is limited connectivity at sea. This can cause time pressure, but as we were always well prepared and transferred in the same area, this was not as big a problem for us as it could be for other vessels.
- The language used by the office is not always clear although we usually overcame this problem. We never experienced a big problem with it.

Prepare Cargo Plan

- A plan is developed for how much cargo is taken from each hold etc.

Contacted by STS Superintendent

- An email is received from the STS Superintendent (e.g. Fendercare) giving more information such as the name of the other vessel as well as more detailed locations and times.

Prepare Equipment on Deck

- We were well setup to conduct a ship-to-ship transfer and it usually only took a couple of hours to prepare all the necessary equipment on deck as everything was already on standby.
- This process would involve things like:
    - Shooting the lines on the deck
    - Ensuring there are extra shackles, heaving lines and mooring lines
    - Making sure equipment is in good condition
    - Making sure the heaving lines are on the right line
    - Making sure lines are shackled up ready to go
- For a one off transfer there would need to be significantly more planning involved. You would need significant time to check all the equipment is present and in good working

order, especially when it comes to moorings. We got quite delayed once because we didn’t have proper mooring lines. It can take weeks to deliver equipment at sea.

- Realising that I couldn’t control everything and being flexible was key. For instance, having back up lines and knowing the risks. Ensure that lines were long enough.

Make Contact with the Other Vessel

- The first contact with the other vessel is typically made on approach when at the rendezvous point.
- A checklist is completed via radio between the two vessels. Although this is usually a formality.

Manoeuvre Alongside Other Vessel

- The biggest challenge will probably be the manoeuvring.
- The mother vessel would maintain a steady course and speed and then give a radio signal to the manoeuvring vessel to come alongside.
- Mooring Master would normally board the manoeuvring vessel.
- Our approach was nearly always made underway. We only made the approach to a static ship with the assistance of other vessels or tugs or on the bunker barge because it was so manoeuvrable.
- We had to abort a couple of times after trying to manoeuvre alongside because the operation was two risky. Swell was the major factor affecting the operation and particularly the resultant relative motions.
- A person with experience would be needed for the first few operations such as a STS Superintendent, Mooring Master or a Pilot. A Pilot may not be required and some Masters would be perfectly placed to do it.
- The manoeuvre of the empty bulk carrier alongside the FHT would be challenging due to the lack of manoeuvrability. When you reverse or travel at low speed you lose control. A bulker in ballast condition is sometimes impossible to manoeuvre at low speed with precision and there are limited options to abort.

- At 0.1 knots you will almost have no control over the vessel. However, at speeds above 0.1 knots you are likely to break the spring lines. Even at 0.2 knots you could break the spring. It is a good idea to have a set procedure with speeds.
- Convincing the export vessel may be difficult as the Captain needs to be comfortable with the manoeuvre. The Captain usually has more power at sea than in a port and either Captain can abort at any time although he would have to answer questions from the company.
- If the vessel is stationary you only have one chance to come in perfect which is difficult, and if you need to abort it might be another hour before you come around again, if you have three or four attempts, half the day is gone.
- The bulkers usually have a stop-start engine with only a limited supply of air. After doing a couple stop starts you can get stressed.

Throw the Heaving Line

- The crew move to the deck an hour or two before. It can be very tedious to wait for the other vessel to come. Can be two hours or more and then you may need to abort. It might be rainy, cold hot, etc. People are tired.
- A heaving line with a weight tied to the end is thrown from the deck of one vessel to the deck of the other vessel.
- The heaving line is thrown by an able seaman who will throw the heaving lines as soon as he can.
- It is very difficult to throw the heaving line the required distance especially in harsh conditions when the manoeuvring vessel could not come as close and the wind could take the line.
- Sometimes the line needed to be thrown 20 times. This caused everyone to get more and more stressed as crews felt the vessels were getting too close. This sometimes led to the need to abort.
- Heaving line could fall on the fender and get tangled on the chain. In this case the line would be lost and you would normally have to make a new line from scratch.
- Often when dealing with heavy mooring lines and wires the heaving line would be replaced by increasingly thick heaving line to prevent the mooring line being dropped.

- Dropping the heaving line is a disaster and you have to start from scratch. The captain will be going crazy.

Let go of Lines

- To let go of the last line you need a stopper, but you don't want to be near it. Have to use a winch to pull it up a bit then release it off the bitt, it's not easy. It's complicated seamanship and not many people learn that in school anymore.
- Experience with stoppers is essential and you need a really good bosun. It took a long time to get used to using stoppers. Letting go of the lines was sometimes a big issue before we figured out how to do it with the stoppers.
- We experience a big problem once when we had let go of all the lines but one and the two vessels drifted apart. The line became too heavy to lift off the bitt and we were running out of line. Both ships grinded the line and they threw it just in time. It could have ended badly because it could have ripped the winch off the deck.
- There is some variability in the sequence of casting off lines.
- Casting off mooring lines could be done better. It is a tricky time.

Transfer the Cargo (In this case liquid)

- We were usually alongside for 12 hours, but the longest we have been alongside is 48 hours. Generally, the whole operation took a day including mooring etc.
- To start the transfer the papers must be in order then both chief officers will agree. There are checklists. The cargo transfer usually worked quite well and better than in a port as both Masters are concerned with things going well. Whereas, the port usually does what they like while Master submits.
- We usually transferred at anchor but if there was a large swell or wind we would have to transfer underway. Transferring in calm weather is much better.
- We never had any serious issue with the cargo transfer that wouldn't happen in a port.
- There was often dirty business with cargo e.g. cheating, not transferring enough.

Make Moorings Fast

- Making the mooring lines fast is not easy and sometimes took half a day or several hours to get vessels alongside, especially if an attempt needed to be aborted.
- We had a forward and aft mooring station although the winch for the forward spring was located so far away there were effectively 3 stations.
- We usually had 2 people on each spring and 4 at the aft and forward station. There weren't enough AB's or OS's so we had to use some engineers.
- A lot of people are needed for mooring as the lines are heavy and you can't always put them straight on the winch - you needed manpower. Maybe a minimum of six people total. If everything is set up well for STS we needed considerably more than that.
- Experience is very important. Those who had done the procedure before knew some good tricks that other could learn from.
- The mooring process is not easy, even if you are experienced. There are so many factors affecting the operation and it was very risky even though no other crew would have done it better.
- There were often problems with the lines.
- The spring line was usually first across unless the Mooring Master indicates otherwise. The Mooring Master often works off a 10-year-old plan which was developed for a one off STS so there is some variability. This was annoying as the Mooring Master often started with a different line to what people were expecting.
- A lot of tension on first spring line. Manoeuvrability is one of the main factors affecting this and also whether you need to abort.
- It could be a challenge to use FHT's spring line initially as the manoeuvring vessel needs to be able to control how much slack is provided to help it manoeuvre.
- The stern line would usually be next after the spring to hold the aft end in. Once these two lines were attached everyone could relax a bit because at least we were beyond aborting.
- When mooring the bunker barge we only needed two people because of the smaller forces and the added manoeuvrability of the vessel. Once you got the forward spring on you were pretty safe.

- With the larger vessels wire lines were used. The wire was heavy and difficult to work with the long lines became very heavy and problematic. We used larger synthetic ropes on the smaller tanker they were over dimensioned and much better.
- We used up a lot of lines which would frequently part. Usually they would fall into the water and we were lucky not to have an accident.
- When the lines parted we threw another one as soon as possible. In bad conditions the lines would part sequentially and we would have to pick up and complete the procedure underway.
- We used 11m tails which also parted.
- We usually had a forward and aft spring, a couple of headlines and a couple of stern lines. A couple of times the headlines were too short when dealing with vessels of similar size, they acted more like breast lines and took most of the strain, causing problems.
- We used hand signals to communicate on deck. Partly because of the language barriers but also because the winch was so far away from where the line was being tendered. This worked perfectly.
- Communication between ships worked quite well but there were some arguments about who's lines to use etc. The crew on both decks, both bridges and both cargo rooms would communicate to each other. Never had any issues, except that there were so many STS transfers it was difficult to find an available channel. The superintendent would usually establish the VHF connection.
- Had radio contact with the bridge, cargo and the other deck crew. Communication was not a problem once we knew what we were doing.
- On the large tanker we normally didn't feel time pressure, but we were stressed. The stress resulted from the complexity of the operation and the dangers involved, perceived or otherwise.
- Heavy lines fly back and forward around your feet, lines parting, people are constantly on their toes.
- On the bunker barge time was a big factor and we did a lot of things we shouldn't have done such as connecting hoses before we were properly secured alongside. They cast off sometimes why we were still attached, which meant we lost control. We took a lot of shortcuts; such as valves open (which should be shut).
- We usually used approaching vessels lines, but this could vary.

- It was useful to be able to top up stores regularly. On the big vessel this was not possible. It would be good to use FHT lines as they can be continually topped up and maintained.
- Not being stressed is important. Lines have to be perfect on the winch. It is important to have the experience and temperament not to get too stressed or stand in the wrong areas.

Make Fenders Fast

- We also had really good fenders on the bunker barge which was really important as it allowed us to come closer without worrying too much. On the big vessel the fenders were big and heavy and towing them was a problem. The chains sometimes broke which meant we had to abort to fix the fender which took forever.
- The Yokohama's were also problematic because they were too heavy for the winches and were difficult to position. Sometimes the boson had to climb down to attach the fenders to the lines being delivered by the support vessel which was dangerous.
- The crew of the vessel had the full responsibility to make the fenders fast, this can be difficult as they take bollard space you might have wanted to use for lines.

Transfer Personnel Between Ships

- The only person transferred would be the surveyor.

Export Vessel Departs

- Officer would give order for disconnect and disembark. The vessel takes off and turns in front of anchored vessel.
- We have had problems with controllable pitch (CP) propellers as they have to start with zero pitch and can move and sway unpredictably.
- To depart the papers had to be completed and signed. Once the other vessel would not lift off after we had checked it, leading to an argument.

Tending Mooring Lines

- There were two guys on deck during operations, one AB one OS, and they would tend the lines and the hose. At points there were more people on deck (at each station) such as in bad conditions or when shifting hoses or holds. But, two people on deck is usually quite ok because you normally have time.
- When line tending you are constantly adjusting line tensions. We knew how to adjust lines from experience and feel, you can hear the lines singing. It can be a problem if you need slack, as eventually you will need to take from the storage drum to the tension drum meaning one line falls in the water.
- Automatic line tendering isn't allowed and is dangerous. The automation behaves unexpectedly, we felt like we lost control and weren't willing to take that risk. The other vessel may not agree or trust the automatic winches and I too would protest if the other vessel planned to use them.
- Manning may be an issue being moored alongside for 4 days plus. After 24 hours we were all dead tired. You would need a surplus of staff for such a long operation. It is exhausting because you are on deck for such long periods.
- The bridge wings touched a couple of time wrecking deck lights and railings. I don't know what caused it. The winds, current and swell often combine into something unexpected. Having a bigger margin would have been really nice.
- It is important to have adequate lighting on deck.
- It is important to have many more spares than in a normal operation.

Interview #3: Marine and Maritime Engineer

Date: 23/09/2016

Background and Experience

- The participant sailed as an engineer for 33 years, working his way up to chief engineer. He worked on a variety of different vessels for P&O Nedlloyd including passenger ships, Ro-Ro's, general cargo and tankers.
- The participant later went into ship building in Japan and Korea, also representing P&O Nedlloyd.
- The participant completed a Bachelor degree in maritime engineering. He has worked as a Senior Lecturer at a maritime university and provided consultancy on the dry docking of ships.

General Issues Working on Bulk Carriers

- I sailed on bulk carriers ranging from 45,000t up to 110,000t. Boredom was the biggest issue as you were chartered for a long time. I tried to get off as soon as possible.
- Cleanliness was a big problem for us as we mixed cargo including edible cargo. This meant we had to clean regularly and the inspections needed to be very thorough.

General Comments about the FHT

- I have seen similar transhipping operation in the US and Canada but didn't think much of it. The concept does however save money because it reduces the requirement to build deep water ports.

Preparing the Engine Room for the Manoeuvre

- Preparing the engine room for the manoeuvre would not differ from what is typical coming into port.
- The electrical supply should be secure. You would normally have two generators or more as you need the redundancy when you are manoeuvring.

- Diesel powered ships are usually quite safe and the computers are reliable and will tell you if something is wrong. The bulk carriers usually only have one propulsion system and testing to make sure everything works is a prerequisite before coming into any port.
- You normally receive an hour's notice prior to manoeuvring. This is not usually stressful and the first half hour is used to correct any problems. Problems found in the second half hour are more time critical.
- The old ships required two people in the engine room to prepare for the manoeuvre. They would run around making things ready. After half hour the Chief Engineer would come down, the supervisor performs a supervisory role and knows from experience how to adapt to the conditions.
- New ships are able to capacitate bridge manoeuvring. Everything is started from the bridge and only the Chief Engineer is required on the bridge. This was the case for the ships we built in Japan and Korea. Not all ships are automated to this extent, but bridge manoeuvring is quite common. Bridge manoeuvring is much better as the old way was prone to time delays and misunderstandings when communicating with the bridge. The Chief Engineer is able to quickly adapt to issues and conditions from the bridge.

Manoeuvring the Bulk Carrier

- In a large seastate manoeuvring is a challenge. It is a high risk operation and you would need an experienced Master and Mate. Initially you might need a Pilot, after a while, the Captain should be given permission to perform the manoeuvre himself if he is suitably experienced.
- Instead of using tugs you can use thrusters to assist with the manoeuvre. The bulk carriers are required to have at least a bow thruster and some even have stern thruster. These thrusters are usually 2-2.5MW which is the equivalent to a fairly powerful tug. Thrusters are a prerequisite if you are not using tugs and are preferable due to the high costs of tugs.
- It is more difficult to manoeuvre in ballast condition. The wind affects you more and the thrusters are less effective and sometimes even stick out of the water a bit. In ballast condition it is advisable to have one or two tugs, although it may be possible without a tug in seas less than 2 metres. Captains have a lot of experience with berthing and will make a decision considering the risks.

- Insurance is a big determiner of whether you need tug/s and a Pilot. The insurance companies may require both to be used. The ports also often require their tugs be used even if there are suitable thrusters, this is in order to cover their costs.
- To abort you have to move as far away from the FHT as possible. In the engine room this is not a problem because you are already ready to manoeuvre. So the Captain is able do what he has to do.
- The shallower water could be an issue in heavy swell and may cause the need to abort.
- Dust can be a major problem when entering bulk terminals. This is evident at places like Kwinana. The dust gets into the accommodation areas, the engines suffer and their filters always gets clogged up. The FHT should not be any worse than a port in this respect. In fact the FHT should be better and allow you to have control of the atmosphere and treat dust properly.

Mooring the Ocean Going Vessel

- Using the FHT winches is a better idea because the FHT is the more stable vessel, the winches can be purposefully designed and it avoids any compatibility issues associated with using the OGV winches.
- You do not necessarily have to use the manoeuvring vessel's lines. While the lines are useful to assist the manoeuvre most of the work is done by the thrusters or tugs. The lines are used more as a backup.
- The winch system must be flexible enough to allow a constant tension in the lines. The automatic line tensioners are great and the modern ones are completely computerised and automatic. The automatic line tensioners are much more accurate than manual line tendering. Manually adjusting the lines is old fashioned and as there is usually only one or two people on the deck you are unable to keep an eye on all the lines at once.

Crew Experience and Communication

- Communication between the officers and the engineers can be an issue. They are like oil and water and don't mix very well. At P&O the officers were dual certified. The duel certificate system is much better; having a common knowledge was fantastic and really assisted communication. It never really worked in Australia as the unions were against it. The increase in Vietnamese, Filipino and Chinese seafarers has effectively seen the system revert to the single certificate system as their training is not set up for it.

- Don't underestimate the Chinese seafarers they have very good training centres. If the crew of the bulk carrier haven't performed a transhipping operation before they might require a Pilot and tug, but with an experienced crew this shouldn't be necessary. Language can be a problem with a foreign crew especially with the Chinese. The engineers typically don't speak any English at all.
- Communication is a more important issue than in a normal port. The procedures act as a common language between the crews of both vessels and are a great help. The domestic crew of the FHT will also be well trained and must accommodate the range of different vessels.
- Procedures are guidelines: The Chief Engineer and Master use the guidelines but as they become more experienced you know when you can have your own input and in doing so you feel freer to manoeuvre the vessel. Crew are always worried about liability if not following procedures.

Transferring Cargo

- If there is too much wind you are not able to transfer, 20-30 knots is about the limit.
- For the FHT the seastate is a bigger problem than the wind and can cause delays. The stability of the FHT would be larger than current transhipper operations due to its wider beam, this means it can withstand greater seas.
- The new methods for transferring bulk cargo greatly reduce the prevalence of dust. The way they treat dust at the Port of Newcastle is great and almost eliminates dust.
- Fire is a risk when transferring bulk cargoes. A silo caught fire in Buenos Aires once which was holding soy. With other commodities dust explosions are a risk.
- The dynamic forces on the ship handling equipment would need to be considered and designed correctly. An experienced crew would know from experience when the forces are too much and would stop transferring before things break down.

Entering the FHT Well Dock

- When the feeder vessel enters the well dock the water can surge.
- The system we would adopt in a dry dock is to use two trolleys on either side of the well dock to guide the vessel in. When the vessel is half way you would add another line attached to a trolley on either side.
- You may however be able to use the feeder vessel's propulsion. The reason we don't do this in dry docks is because you have blocks in the water that may be knocked over. The amount of water you have around you will determine whether or not you can use the propeller.
- Cruise ships often have four propellers except the two azipods are in the middle. My feeling is that having the azipods in the middle would be more efficient than on the outside.
- You should not rely on ropes to secure the feeder vessel in the well dock. Instead you should utilise a hydraulic mooring system to hold the feeder vessel in place. The hydraulic mooring system prevents the vessel from rolling or swaying while the friction on the pads dampens the motion in heave and pitch.

Marine Inquiries

- I was involved in the marine inquiry following the Anro Asia grounding. We were grounded on the rocks for 9 days while chinooks lifted 78 containers to shore to lighten the vessel. The incident caused significant damage to the vessel.
- The Pilot went the wrong way and was found guilty (suspended for 3 months). The Pilot initially tried to blame the steering gear, we knew this was a common tactic so we sealed the area off to prevent access and tampering. The morning following the grounding there were lawyers on the deck. The wanted to look at the steering gear but had to wait for our lawyers.
- The court of inquiry took a long time to find the Pilot guilty.
- The court of inquiry was conducted fairly and the verdict worked out very well for us.
- There is no problem with combining safety and judicial purposes in the inquiry.

Australian Transport Safety Bureau (ATSB)

- The ATSB do their job in a professional manner.
- Testimony given from the crew should be permissible in legal proceedings.

The Seafarers Role in Safety Investigations

- Courts of inquiry are not fun and are constantly in the back of the seafarer's mind.
- The court of inquiry can take away your livelihood. It takes a long time to get your certificate and it can be taken away in the blink of an eye.
- The seafarer is often used as a scapegoat for the company and is caught between a rock and a hard place: AMSA who want procedures to be followed and the company who wants profit.

Automation

- Automation definitely assists the seafarer. The statistic that 80% of all marine accidents are caused by human error is correct and is an argument for automation.
- Automation works more accurately and can adjust to conditions more efficiently than humans. Sometimes automation can go too far and while it helps the seafarer you always need to be wary that automation can fail.
- The cost of automation is very expensive. To fully automate a vessel is about $3,000,000 and the cost is an important factor in the design. It can be cheaper to pay the additional labour costs especially for bulk carriers which have a lifespan of only 15 years. As a result, bulk carriers are less automated and less safe than longer life vessel such as cruise ships.

Interview #4: Principal Naval Architect / Seafarer

Date: 09/08/2016

Background and Experience

- The participant holds qualifications in both naval architecture and seafaring.
- He has over 40 years experience in the marine industry, including Principal Naval Architect and CEO of a ship design company.

National Standard for Commercial Vessels (NSCV)

- While the NSCV is good in theory is does not work well in practice. The major problem with the NSCV is that it doesn't account for variation between States.
- Australia's large size means that there are huge differences in the number and nature of commercial vessels operating in each state. In Queensland, for example, there is a huge discrepancy between the number of recreational vessels (not covered by the NSCV) and the number of commercial vessels. There are also differences in weather conditions and many other external factors. The old system allowed for this State variation and worked quite well.

Safety Investigations

- The point of a safety investigation is to ensure that an incident or accident doesn't happen again. However, the majority of marine inquiries conducted over the last 40 years have had very strong political influences and motivations. The removal of the provisions for a board of marine inquiry is a good thing as it assists in removing some of the political influences. These extraneous factors have been effectively removed from accident investigations by adopting the AMSA/ATSB model for accident investigation.
- A safety investigation can be combined with a judicial purpose to reduce reinvestigating the same event twice and because the cause of an accident is often the same as the event responsible for the accident. There is also no reason why the information and testimony given by seafarers should be made publicly available and this should happen.
- Experienced officers and seafarers are the most qualified people to conduct a safety investigation. An experienced and qualified officer will always come to the same

conclusion for an investigation relating to a marine accident of incident. Typically, the investigator knows where the blame lies prior to the investigation being conducted, and the investigation is simply a way of following the correct channels.

- At the same time there is still a lot of guessing involved in safety investigations and a degree of people leading investigations in a preferred direction. However, technological developments over the past decade have assisted in reducing the uncertainty in investigations and have been instrumental in improving the standard of accident investigations.
- A breech in COLREGS or another regulation automatically makes that vessel at fault. These regulations are dumped on the officer of the watch. For example, the cause of a collision between two speed boats on the same week as the Wunma incident was 90% human error because the collision regulations were not followed. While human error is noted as a primary cause in 80% of marine accident investigation this should be a starting point for further investigations.

The Wunma Incident

- The Wunma incident should not have resulted in a board of marine inquiry. The event was an incident, not an accident and the push for a marine inquiry was led by unions and politicians in order to serve political agendas. There was a subsequent 'feeding frenzy' of lawyers who acted to expand the scope of the inquiry and unnecessarily prolong its completion. For these reasons I had a general distain for the process and did not follow the proceedings closely.
- The proper course of action following the Wunma incident would have been for the ATSB to review the incident following a course of action which is in keeping with similar events. Following the Wunma inquiry it was poor form for the unions to use the recommendations as a political tool to slander Marine Safety Queensland and such behaviour should not be allowed.

Other

- Over the past 20 years the vast majority of new regulations from the IMO have been concerned with the environment rather than vessel safety. These environmental regulations have had a negative impact on ship safety and accidents have been caused by officers foregoing safety when trying to comply with environmental regulations.

Interview #5: Naval Architect 1

Date: *09/08/2016*

Background and Experience

- The participant is a naval architect, with seagoing experience.
- He has direct experience and familiarity with the FHT concept.

OGV-FHT transfer

- It is currently thought that a Pilot would be required to manoeuvre the OGV alongside the FHT. The primary reason for this is that the foreign Master of the OGV may not have the required ship handling abilities to safely complete the manoeuvre. The Pilot transfer is not different or unusual from any existing operation and will most likely occur once the OGV reaches shallow water. A helicopter is the most likely and the most preferable means of transporting the pilot to the OGV but this depends on location and distance from the shore.
- The communication between the two ships is a major source of variation and often leads to significant performance variation. Communication will likely be light until the Pilot is transferred onto the OGV. After the Pilot transfer the two vessels will be in constant contact with each other. Both Masters usually have an equal say when assessing the conditions but this is a grey area and has led to arguments and miscommunications in the past. Occasionally the decision will be left to a single Master (usually the manoeuvring master). The communication between the two vessels is somewhat simpler than existing transhipping operations (such as the Wunma or the Abburi) and is likely to lead to fewer issues. It was suggested that Ken McLane from P&O Maritime is a good person to speak to for further information regarding communication during ship-to-ship transfer operations.
- The preliminary planning for the operation is usually arranged by the shipping agency. Once the OGV is alongside the FHT the First Mate of the FHT will usually go aboard the OGV to brief the crew of the transfer operation. For the first loading of an OGV a surveyor will also likely be required to be present although this could potential take place at the OGV’s last port.

- The engines for the FHT thrusters will be constantly in operation throughout the whole procedure. The engines will be utilised both to move the FHT in the event of an emergency and manoeuvre and steady the FHT while the feeder vessel is entering and exiting. The ability for the FHT to manoeuvre out of the way is limited by the range of motion allowed by the SPM. However, the thrusters should be quick to react as they have been designed to be able manoeuvre both the FHT and OGV.
- The engines will not however be utilised to manoeuvre the FHT alongside an anchored OGV. Pilots have indicated that it is more favourable to manoeuvre the OGV directly alongside a stationary FHT of similar size. It is generally well within a Pilot’s abilities to manoeuvre the OGV within 10-15 metres of the FHT. The course of action is unlikely to be the same for the mini FHT. It is more likely that the mini FHT thrusters will be used to manoeuvre the vessel alongside the OGV at anchor.
- The static operation is not likely to present any more difficulties over an operation where both vessels are moving forward and similar operations already exist in Moreton Bay, Queensland, with the transhipment of LNG.
- Whether fixed fenders or Yokohama fenders are used is a matter of debate. The fixed fenders are longer wearing but are much more difficult to change compared to the Yokohama’s. It is likely the fendering system will include a combination of both fixed and Yokohama fenders with the majority of the load being taken by the Yokohama’s. It is anticipated that davits will be placed along the length of the FHT to allow the Yokohama’s to be replaced easily.
- Most pilots have stated that the manoeuvring of the OGV alongside the FHT would not require tugs. The costs of having tugs on standby and in operation are significant and should be avoided if possible. Pilots have indicated that tugs may be required in winds exceeding approximately 25 knots however is may be more cost effective to anchor off until conditions become more favourable.
- Once the OGV has been manoeuvred alongside the FHT the heaving lines from the higher ship would normally be thrown (usually this would be the unloaded OGV). Both ships would have sufficient heaving lines for the required operation. The mooring lines used would probably be the FHT’s normal synthetic lines. Most OGV’s will have sufficient bitts and fairleads for the operation. There may however be some compatibility issues as the FHT fills the various OGV holds. This was the case with the Wunma which required the OGV lines to be used when filling her aftermost hold. It is much more

preferable to utilise the FHT's lines as it allows the OGV's holds to be filled correctly without having to communicate with the other Master.

- It is suggested that self-tensioning winches will be utilised as a means of automating the line tendering operation and reducing the amount of labour required. Walking may be an issue but smaller operations have used a similar arrangement.
- The OGV should be alongside and discharging within half an hour from the time she starts manoeuvring.
- The FHT is constantly manned with appropriate accommodation. The crew is intended to be around 8, maybe a few more. There would maybe be one person in the discharge room with one more monitoring the material transfer. There would be two persons on deck monitoring lines. The FHT does not need the full complement required of an ocean going vessel as it is essentially just a shed and the material handling technology is highly automated. This is also dependent on a confidence that SPM system can hold in the event of a cyclone. Being an ocean going vessel the OGV usually has an abundance of crew.
- The material transfer will generally take 3-4 days to complete, although this time may be reduced to 2 days depending on how close the operation is to shore and how many feeder vessels are in operation. The material will generally be reclaimed straight from the feeder vessel when it is docked and from the FHT stockpile when the feeder vessels are in transit. In order to optimise the operation, there may be time when no material is being transferred while awaiting a feeder vessel. The reclaiming system transfer rate varies depending on product but for iron ore the discharge rate is expected to exceed 3,000-3500 t/h for each reclaimer or almost 7000 t/h if two reclaimers are used.
- The departure of the OGV is a lot easier than the approach. It is likely that the FHT thruster will be used to swing the FHT away from the OGV and break any pressure holding the two vessels together.

The Big Picture

- Breaking down industry resistance to new technology is one of the major challenges facing the FHT. Most companies accept that the concept is the most efficient means of transhipping but are unwilling to commit to untested technologies.
- The global downturn in the price of commodities has benefited the FHT as justifying the costs for significant infrastructure has become more difficult.

- Environmental considerations are extremely important and can easily stop a project. The pre-existing attitudes regarding the environmental impact of transhipping systems can be difficult to break down. The environmental merits of the FHT have garnered support from major environmental agencies such as the Great Barrier Reef Marine Park Authority.
- The FHT is more suited to the heavy density bulk products like iron ore or even bauxite. Lighter products like coal would not allow the same holding capacity or material transfer rate.
- Within Australia the majority of interest typically comes from the smaller miners however the FHT (or even the implementation of multiple FHT's) has a very large window of viability and can still prove the most beneficial means of transhipping for very large mines up to 80 MT. A large mining company in Canada is looking at the FHT as an alternative to having to transport product into the United States for export. There are a large variety of factors which affect the viability of the concept given a particular location these include access to rail, roads and ports as well as the distance to the shoreline.
- While the FHT concept promises major benefits to mining companies in Australia, the flexibility of the FHT also makes the concept appealing in countries which are politically unstable and Africa has emerged as a particularly likely prospect. South America is also a potential candidate, due to the control of the ports by the major mining cartels.

Interview #6: Naval Architect 2

Date: 09/08/2016

Background and Experience

- The participant is a naval architect with 30 years experience.
- He has direct experience and familiarity with the FHT concept.

Technical Aspects of the FHT

- The biggest influence on the viability of the FHT concept is the ability to break down industry resistance without a track record. The concept extends beyond the scope of what is typical in transhipping today. Despite this the gaps which exist have all been bridged in other areas. For example, the ship handling required to manoeuvre the OGV alongside the FHT is outside what is typical in current transhipping operations but within a normal operational envelope in others fields such as oil and gas. The challenge lies in combining and implementing the technology from other areas. Fusing the advice from the various experts can be challenging. Most experts are concerned with optimising a single component of the system without considering the big picture.
- Many experts find their envelope being pushed by the FHT. This is most apparent when traditionally land based equipment is being applied to a floating platform. The materials handling is a particularly challenging example. The adaption of the materials handling system to a floating platform is the greatest challenge for the FHT. Corrosion, accelerations and motions are some of the main issues.
- The best remedy to these challenges is to work through every component meticulously in order to better understand weaknesses, interactions and overlaps. An understanding of the broader system can be achieved using risk assessments and mind maps.
- Aside from the resistance to new technology the environmental factors are the next most influential and the FHT concept has found unexpected friends from the environmental movement. The FHT is the most preferable option both financially and environmentally.
- When assessing and designing the FHT, it is useful to be able to draw on experiences with the Wunma and the Aburri. Getting first hand feedback from the crew allows us to understand how operations are managed and controlled. It is always important to

consider the testimony of Masters and crew members carefully as these judgements are often heavily influenced by prior experiences.

- The most surprising difference between the design and the operation of the Wunma and the Aburri was how the vessels stand off and constantly adjust their position relative to each other. This is in order to correctly fill the holds of the OGV. It is not uncommon to have the thrusters operating in one direction while the winch is hauling in the other. The relative movement will still occur to a large extent with the FHT. The movement required can be reduced by using telescopic booms, but this adds mechanical complexity and additional maintenance requirements. The standing off has the added benefit of controlling the wave interaction between the two vessels.
- As with all ship handling the FV entering the FHT is a somewhat subjective operation. Five different captains will perform the same operation in five different ways. Some use four thrusters, some will use only two, some use a lot of rudder, some hardly any. It is important to cater for the range of operating styles which all fall within the realms of what is considered good seamanship. The Wunma for instance has both a tunnel valve thruster and a pump jet to give the operator options.
- Fendering and well dock design is another way of controlling the feeder vessel entering the well dock. The fendering system design is most advanced on the mini FHT. The design has to accommodate for draft variation, roll angles and many more variables. The design is funnelled to allow the Master of the FV to bump their way along if required. It would be preferable to work with an auto lock system rather than mooring lines in the well dock but development is still required regarding this concept.
- Pilots have indicated that the Masters of Cape class ships sailing under foreign flags do not possess the ability to manoeuvre their vessel alongside the FHT and that a pilot would be necessary for the manoeuvre. The mini FHT is more likely to manoeuvre alongside the OGV at anchor. The mini FHT is designed for edible grains which also presents specific issues. The mini FHT will subsequently operate on a seasonal basis.

Broader Picture

- Once the first FHT becomes operational the flood gates are very likely to open and many more will follow. An enormous amount of effort will be put into making the first FHT a success.

- The FHT can be applied to many materials by varying the materials handling system. The same limits on specific gravity and consistency which apply to the materials handling system on land also apply to the FHT.
- For some mines shipping is the greatest cost incurred, because of this the mine does not necessarily need to be located close to the shore for the FHT to be the most cost effective option. The FHT has the potential to make small, high grade or short life mines feasible. The relocatablility of the concept is one of the main selling points. This advantages mines with a short life and smaller throughputs as well as those located in areas of political instability.